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Sump Studies II - Geothermal Disturbances in Permafrost Terrain Adjacent to Arctic Oil and Gas Wellsites

Northern Affairs Program

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SUMMARY

Two sumps, one at the Panarctic Bent Horn 1-01 wellsite on Cameron Island (76°N, 104°W) and the other at the Gulf Ogruknang M-31 wellsite in the Caribou Hills (69°N, 134°W), were instrumented during the 1976-77 winter to monitor geothermal conditions in the enclosing permafrost. Numerical simulation based upon observed field data is used to predict geothermal changes. Bent Horn 1-01 was a one season winter drilling operation; Ogruknang M-31 was a two season winter drilling operation in which the sump was left open during summer and infilled during the second winter.

At 1-01 sparse data indicate that sump fluids froze virtually instantaneously upon entering the sump and have remained frozen after site restoration. At M-31 the sump fluids were not completely frozen at the time of infilling. At both sites, permafrost temperatures beneath the sump rose significantly during the period of well drilling. Data from M-31 indicate (a) temperatures at a depth of 0.5 m below the sump floor rose rapidly from -14 to -4°C during the early stages of sump use and then rose slowly to -0.5°C by mid September 1977, (b) thawing of permafrost during the summer of 1977 was restricted to the sump walls, (c) at a depth of 2.5 m below the sump floor geothermal disturbances became minimal, and (d) by July 1978, temperatures at a depth of 2.0 m below the sump floor had achieved a quasi-equilibrium of -1 to -2°C.

These data suggest that the use of below ground sumps to contain waste drilling fluids at the two localities described does not lead to permafrost degradation, and that sump fluids, if not completely frozen at the time of infilling, eventually freeze *in situ* in the permafrost. In areas of warmer permafrost and/or higher summer temperatures, the same conclusions may not apply.

1. THE ALUR SUMP PROJECT

One of the objectives of the ALUR sump project is to provide environmental and geotechnical information related to the construction, use and subsequent restoration of sumps in different permafrost and terrain situations. A further objective is to assess methods of alternate disposal of waste drilling fluids, particularly direct spillage on the tundra. A long term objective is to evaluate the effectiveness of the Arctic Land Use Regulations as they relate to the drilling of oil and gas wells in permafrost and the disposal of drilling fluids.

There are four phases to the project.

The first phase was undertaken during the summers of 1976 and 1977. A survey was undertaken of old and active wellsites in the Arctic, of varying ages and located in a variety of terrain and permafrost environments. The objectives were to identify reasons for the failure or non-failure of sumps, to develop case histories and documentation upon sump problems, and to identify localities where drilling without a sump may have been preferable.

A second phase of the project, undertaken during the winter of 1976-1977, consisted of the instrumentation of two sumps in order that the thermal, permafrost and geomorphic changes associated with the operation, restoration and subsequent abandonment of the sumps could be monitored. Of particular interest were (a) the influence of sump fluids upon permafrost thermal regimes, (b) the determination of whether sump fluids freeze in situ or not, and the time period involved, and (c) the nature and extent of any thermokarst activity that might result. One sump, at the Panarctic Oils Ltd. Bent Horn 1-01 wellsite on Cameron Island was instrumented in November 1976. A second, the Gulf Canada Ltd. Ogruknang M-31 sump in the Caribou Hills, Mackenzie Delta, was instrumented in April 1977. Monitoring of these two sites, at varying levels of intensity, was continued into the summer of 1978.

A third phase of the project involved the development of numerical simulation models illustrating the thermal effects of sump fluids upon the enclosing permafrost. The models generated were tested against the field data obtained from the instrumented sites.

A fourth phase of the project involved a consideration of the toxicity and vegetation effects of waste drilling fluids. An experimental spillage of sump fluids was undertaken at the Gulf Siku-21 site in the Mackenzie Delta in January 1978 in a locality where a detailed botanical and site inventory had been made the previous summer. In addition, visits to a number of old wellsites in both the High Arctic islands and the Mackenzie Delta were made during the summer of 1977 to investigate the effects of leakage of drilling fluids, and to develop case histories.

Personnel involved in the ALUR sump project are Dr. H.M. French, Department of Geography and Regional Planning, University of Ottawa, responsible for project co-ordination and field studies, Dr. M.W. Smith, Department of Geography, Carleton University, responsible for computer simulation studies and field studies, and Dr. D. Smith, Department of Botany and Genetics, University of Guelph, responsible for the biologic and toxicity aspects.

The first report (French, 1978a) relates only to the first phase of the project, and provides background information upon the sump problem together with observations and conclusions made during the 1976 and 1977 sump surveys. The second report describes the thermal monitoring programs undertaken at the Bent Horn 1-01 and Gulf Ogruknang M-31 sites, and compares the field data with computer simulated data. A third report outlines the nature of the toxicity, vegetation and other effects of sump fluids.

2. INTRODUCTION

Permits issued under Territorial Arctic Land Use Regulations require that drilling fluids be contained completely in below ground sumps, and that these sumps be infilled upon completion of the well, so that the drilling fluids should freeze *in situ* in the permafrost. A number of standard bioassay studies suggest that sump fluids may pose environmental or toxicity problems. Although there is variation in the composition of drilling fluids, and changes are continually taking place, it seems on balance that sump fluids are not a positive attribute to the tundra environment and their containment is to be generally preferred.

French (1978b, 14-16) has described some of the terrain and environmental problems associated with the use of sumps. They are briefly summarised here. One group of problems relates to the thermal influence of the sump fluids upon the enclosing permafrost. Melting of permafrost may occur around and beneath a sump. This is not a major problem if the well is drilled during the winter months since the fluids usually freeze quickly in the sump. During a summer drilling operation, however, or when a sump is left open during the summer, serious problems may result. If the enclosing permafrost is ice-rich, the possibility exists for substantial enlargement of the sump, with slumping of the sump walls. As a general rule, the amount of subsidence and the rapidity of the process will vary depending upon the amount and distribution of the ground ice, the nature of the enclosing materials, and the air and ground temperatures at the site.

A second group of problems relates to non containment of waste drilling fluids.

In certain instances, the sump walls may expose ice wedges or ice lenses in the permafrost. This raises the possibility of fluid escaping by, for example, preferential thawing along ice wedges. The rate of gullying and headward extension associated with ice wedge melt can be rapid, and such erosion may lead to serious undermining of the rig structure itself. Insulation techniques are used to combat this problem; in the Mackenzie Delta for example, Shell Canada sump construction manuals suggest the use of 2.4 cm thick preformed slabs of polyurethane foam to be placed against the walls and dykes (Argument, 1973, p.8).

The presence of a lot of ground ice may lead to excavation problems. Usually a sump is blasted with high explosives and the material is removed using heavy earth moving equipment. The presence of substantial quantities of ground ice within the permafrost (e.g. ice wedges, massive icy bodies) may reduce the effectiveness of the blast, on account of the different elastic properties of ice and mineral soil. Thus, the initial sump may not be as large as planned. In such cases, the volume of fluids may be such that an additional sump is required.

The third, and most common, group of problems relates to the infilling of the sump and site restoration*. The usual procedure is for the original sump infill material, which is heaped to one side during construction, to be used as backfill. This restoration is undertaken in winter when the movement of heavy vehicles over frozen tundra does relatively little damage. If the sump has been left open during the summer, or if the drilling is in summer, infilling is not usually attempted until mid or late winter, when the sump fluids are frozen sufficiently to bear the weight of the overburden. A doming of the infill over the sump is usually practised in order to compensate for any subsidence. French (1978a, 36-37) had documented a number of specific problems:

(a) The 'volcano effect' which occurs during sump infilling when the fluids are not completely frozen. The surface breaks under the weight of the overburden, allowing fluids to squeeze to the surface.

(b) Sump subsistence and collapse which usually occurs during the summer following restoration. This reflects the incorporation of snow/ice in the infill and/or seepage of water downslope into the sump in summer.

(c) A lack of infill resulting from melt-out of ice during summer from sump infill material and a loss of volume. The depression so created promotes a standing water body over the sump which serves as a 'heat-sink'. This problem is particularly acute in areas where there is a lack of accessible aggregate.

(d) Leakage of fluids. This may occur if ice lenses in the sump walls melt out or if the sump is too full upon infilling leading to seepage through the active layer.

(e) Poor geographic location. An example is a sump located in a water course where erosion of the sump and fluid release is a distinct possibility.

(f) Severe terrain disturbance. This is usually associated with summer operations occurring in well-vegetated ice-rich tundra and/or where additional sumps were constructed and/or where technical drilling problems were encountered.

*Editor's note: 'Site restoration' is a term commonly used by industry but the implication of returning the site to the previous condition is generally unattainable. Rehabilitation would be a more appropriate objective.

3. PRESENT OBJECTIVES

In addition to, and following upon, the reconnaissance survey of old wellsites in the Arctic Islands and the Mackenzie Delta (French, 1978a), a need for more specific information was identified, in order to ultimately establish effective criteria to minimise the effects of waste drilling fluid disposal in these regions.

There is very little quantitative data on the environmental effects of sumps, and no comprehensive set of observations from single locations covering all phases of sump operations and restoration. Thus a sump monitoring program was developed, involving the two geographical locations mentioned above, and two different drilling timetables. The program was designed to address the problems identified and documented by French (1978a). In particular, the rate at which waste drilling fluids freeze, and the thermal effects which both sump construction and the drilling fluids have upon the enclosing permafrost are unknown. Two new drilling locations were selected (see below), along with adequate instrumentation and control, to document the thermal and environmental effects of sumps during the drilling operation and subsequent to site restoration. The baseline data have also been used in a computer simulation analysis, to assess the general geothermal effects of sump operations carried out according to present Arctic Land Use Regulations.

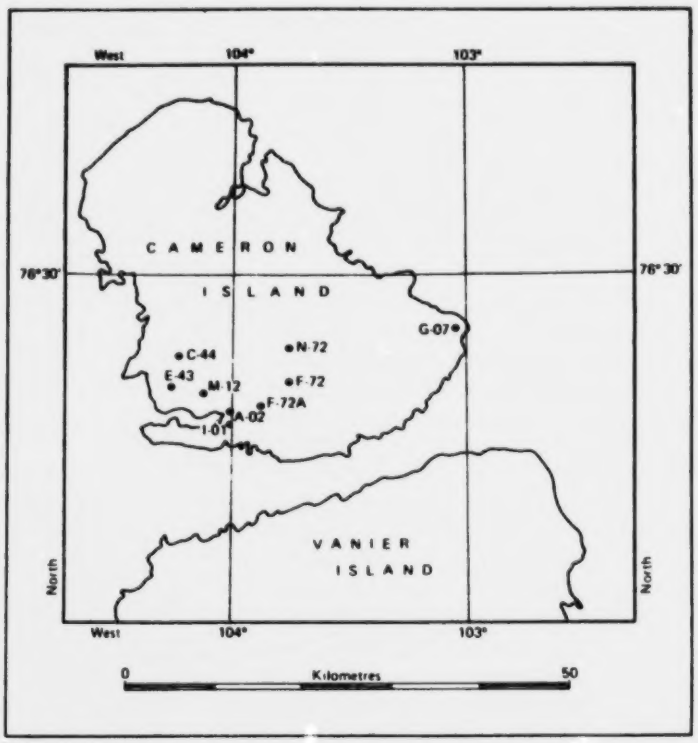


FIGURE 1 A. Location of Panarctic Oils Limited Bent Horn 1-01 wellsite, Cameron Island, High Arctic.

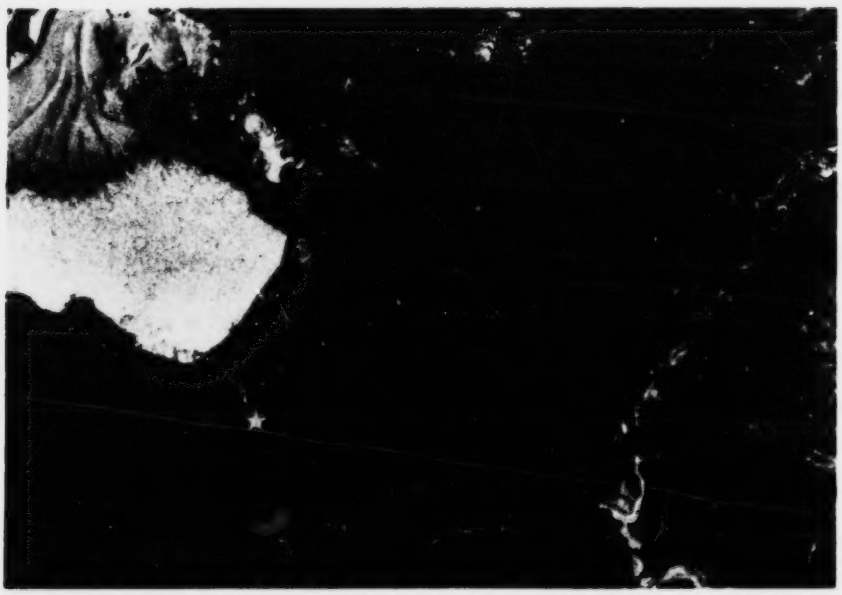


FIGURE 1 B. Air photograph, Bent Horn area, southwest Cameron Island (A 16761-122) showing location of 1-01 wellsite.

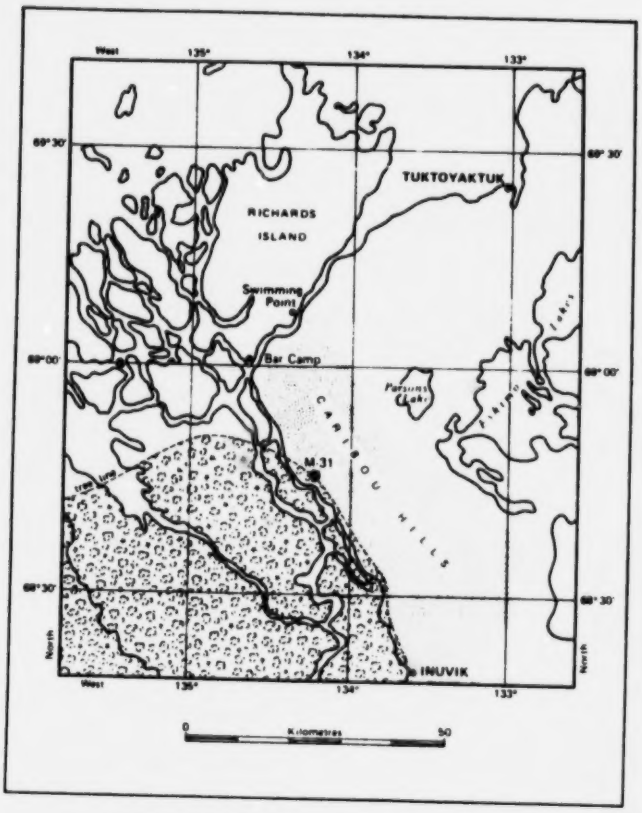


FIGURE 2 A. Location of Gulf Canada Limited Ogruknang M-31 wellsite, Caribou Hills, Mackenzie Delta.

FIGURE 2 B. Air photograph, west side of Caribou Hills (A 24053-52) showing location of M-31 wellsite.

FIGURE 3 A. Oblique air view looking north of vegetated tundra terrain in vicinity of Bent Horn Southwest Cameron Island, August 14, 1977. Note well developed seepage lines.

FIGURE 3 B. Ground view of terrain at Bent Horn with 1-01 wellsite in background, August 11, 1977.

FIGURE 3 C. Oblique air view looking west of Gulf Ogruknang M-31 wellsite after site restoration, August 4, 1978. Note large polygonal network of frost fissures at the site. East channel of Mackenzie River in the background.

FIGURE 3 D. Ground view of terrain adjacent to the Ogruknang M-31 wellsite showing shallow troughs associated with the frost fissures and willow-tundra vegetation, August 4, 1978.

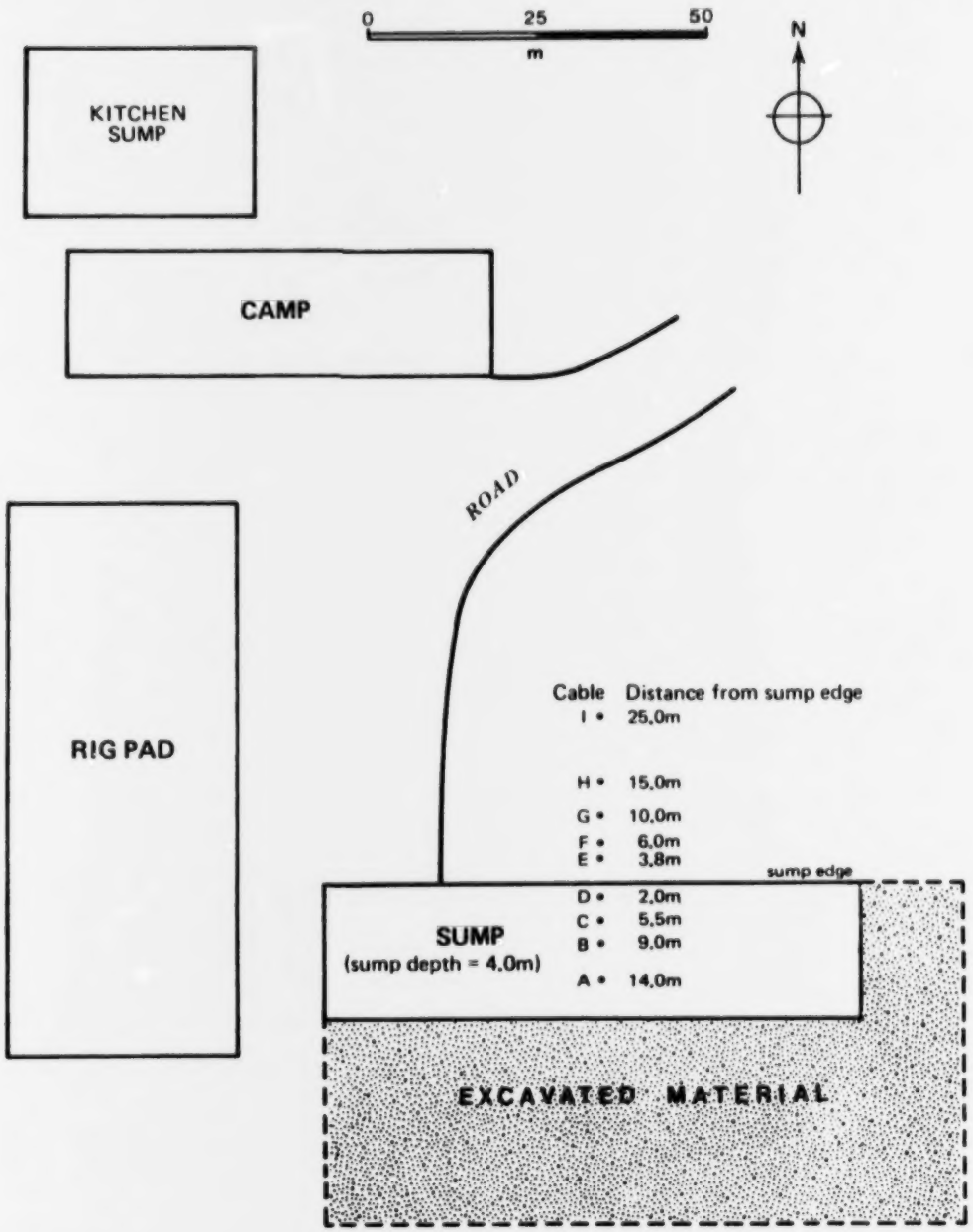


FIGURE 4. Plan of wellsite layout, Bent Horn 1-01 wellsite, Cameron Island.

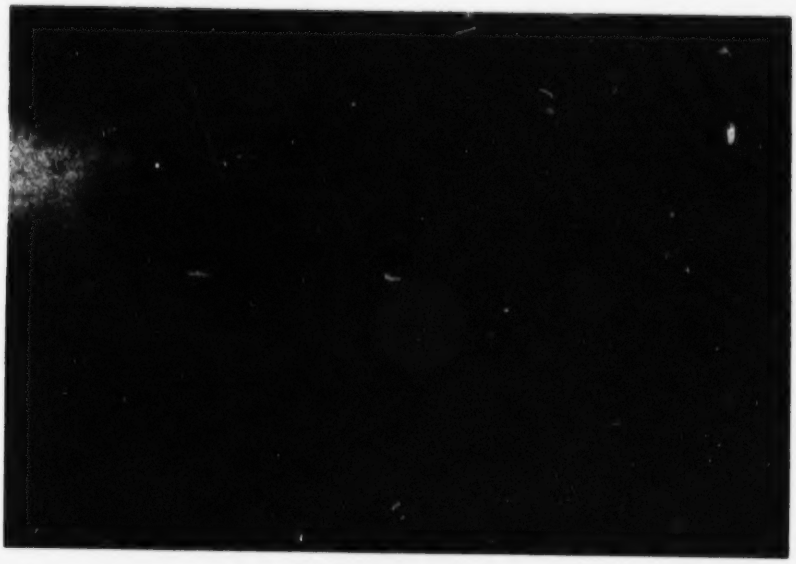


FIGURE 5 A. Bent Horn 1-01 wellsite. Blasting of the sump, November 2, 1976.

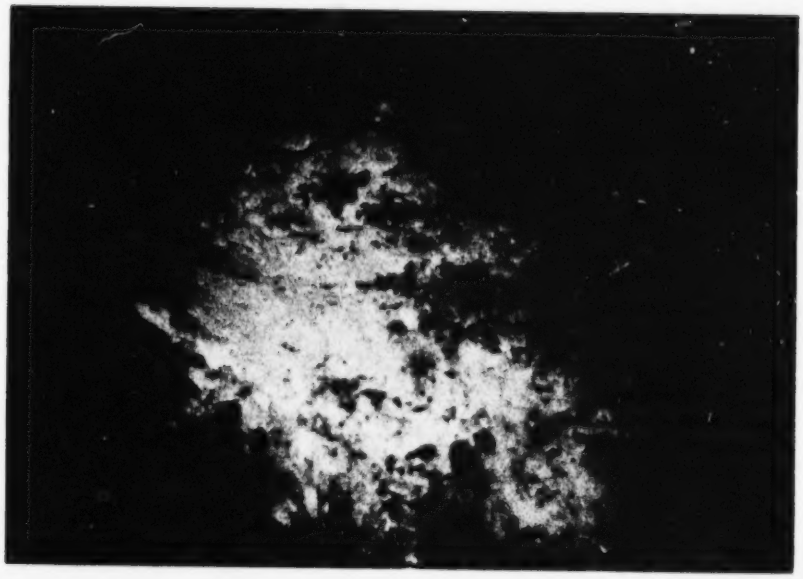


FIGURE 5 B. Bent Horn 1-01 wellsite. Ice wedge exposed in sump wall at time of sump construction. The wedge is seen in oblique section and the blast has destroyed the ice foliation. Enclosing material is glauconitic sandstone, November 5, 1976.

FIGURE 5 C. Bent Horn 1-01 wellsite. Drilling boreholes with seismic rig in sump floor, November 6, 1976.

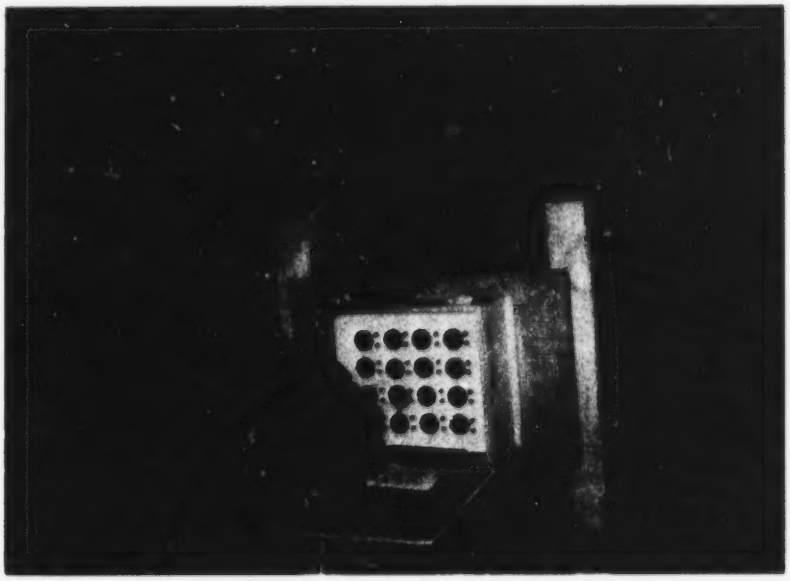


FIGURE 5 D. Bent Horn 1-01 wellsite. Completed instrumentation panel for thermistor cables, November 8, 1976.

4. THE GEOTHERMAL MONITORING PROGRAM

Two sumps were instrumented during the winter drilling season of 1976-77, one at a High Arctic site (Cameron Island) which operated entirely in winter, and a second at a Low Arctic site (Caribou Hills, Mackenzie Delta) where operations extended over spring, summer and winter (Figures 1, 2). In addition to the differences in timing, the two sites pose different ecological implications for drillsite operations (see Smith, D. Sump Studies III - in preparation). The choice of the actual sites was left to industry, bearing in mind their logistics.

4.1. Panarctic Bent Horn 1-01 wellsite, Cameron Island

The Bent Horn area is low-lying, gently sloping (generally $<4^{o}$) and well vegetated (Figures 3A, 3B). It is not typical of most of Cameron Island, which is moderately dissected, sparsely vegetated, and where polar desert soils (Tedrow, 1977) predominate. The terrain conditions in the Bent Horn area are described in more detail in French (1978a, 17-21). Temperatures recorded at the adjacent Bent Horn N-72 wellsite indicate the permafrost to be $-15^{o}C$ at the 50 m depth (Taylor and Judge, 1977). Since this wellsite is located approximately 1 km from 1-01, and in similar terrain, one may assume undisturbed permafrost temperatures at 0-01 to be similar. These temperatures are typical of those recorded elsewhere in the High Arctic islands (Judge, 1973; Mackay, 1974; Brown, 1978).

The sump at 1-01, which measured 80 x 20 x 4 m (Figure 4), was constructed in October 1976, and instrumented at that time (Figures 5A, 5B, 5C, 5D). Drilling lasted until April 1977, and the sump was infilled in May, 1977.

The sump was constructed mainly in bedrock (consolidated sandstone) which reaches to within one metre of the surface. This bedrock is overlain by a veneer of coarse gravel and/or bedrock fragments and a surface organic layer, primarily of moss. This organic mat is typically 5 - 15 cm thick and can be peeled away. It provides excellent insulation to the underlying permafrost - French (1978a, 17-18) reports active layer thicknesses of only about 12 cm in August 1977.

A well developed ice wedge network dissects the bedrock. The wedges are 2 to 3 m deep, 5 to 10 m apart, and 1 to 2 m wide at the top (Figure 5B). Because of the organic insulating layer, the tops of ice wedges are found within 15 cm of the surface. When the sump was constructed, the presence of this ice edge network reduced the effectiveness of the blast and the sump was reduced in size.

4.2. Gulf Ogruknang M-31 wellsite, Caribou Hills

The Pleistocene Mackenzie Delta is composed of undulating, sometimes hilly, terrain, with numerous lakes, drained lake basins and pingos (see French, 1978a, 22-29). The underlying material is mainly silt, sand and gravel. Mean annual ground surface temperatures of between -5^{o} and $-7^{o}C$ are recorded from wellsites and seismic shot holes in the Caribou Hills (Mackay, 1974; Taylor & Judge, 1977). Although ice amounts can be as little as 10% by volume, massive icy beds, several metres thick, are common. High ice contents in underlying materials is the major problem associated with sumps in this region. Ice may be exposed in sump walls, and melt out if left open in summer, thus leading to sump enlargement.

The sump at M-31 was constructed in February 1977. It was compound in shape (Figure 6) with a dividing wall separating the sump into two sections. The main section, measuring 67 x 30 x 5 m was instrumented in April 1977 (Figures 7A, 7B, 7C, 7D). Drilling was carried out over the summer and finished in August. The sump was infilled in late February and early March 1978.

The sump was constructed in a complex of fluvio-glacial sand and gravel, which contained small amounts of silt and clay at some depths (Figure 8). Massive ice was present at a depth of between 7 to 12 m - i.e. 1.5 to 2 m below the sump floor but ice contents in the upper 7 m were quite low (10-15% by volume). This was considered fortunate since massive ice exposed in the walls of other sumps in the Parsons Lake area have resulted in either melt-out problems during the summer (eg. Gulf Parsons Lake A-44) and/or leakage of fluids (eg. Gulf Parsons Lake N-20) (see French 1978a, 26-28). However, the massive ice present below the sump floor was of concern since, if allowed to melt over the summer, it would result in substantial enlargement of the sump.

4.3. Instrumentation

At both sites, thermistor (YSI 44033) cables were installed at the time of sump construction for ground temperature information. Drilling was done with a seismic rig (Figures 5C, 7C). A transect was set up, running out from the middle of the sump to a point where no thermal disturbance would be expected (Figure 9). Attention was concentrated around the sump wall, although it was not practical to drill any closer than about 1.5 m. It was assumed that effects on one side of the sump are generally mirrored on the other side; it is thus considered as a half-space problem. The thermistor boreholes were drilled to 15 m, a depth at which no detectable thermal disturbance would be expected over the life of the sump. Thermistors were located at depths of 0.5, 1, 2, 3, 5, 6, 9, 10, 12 and 15 m.

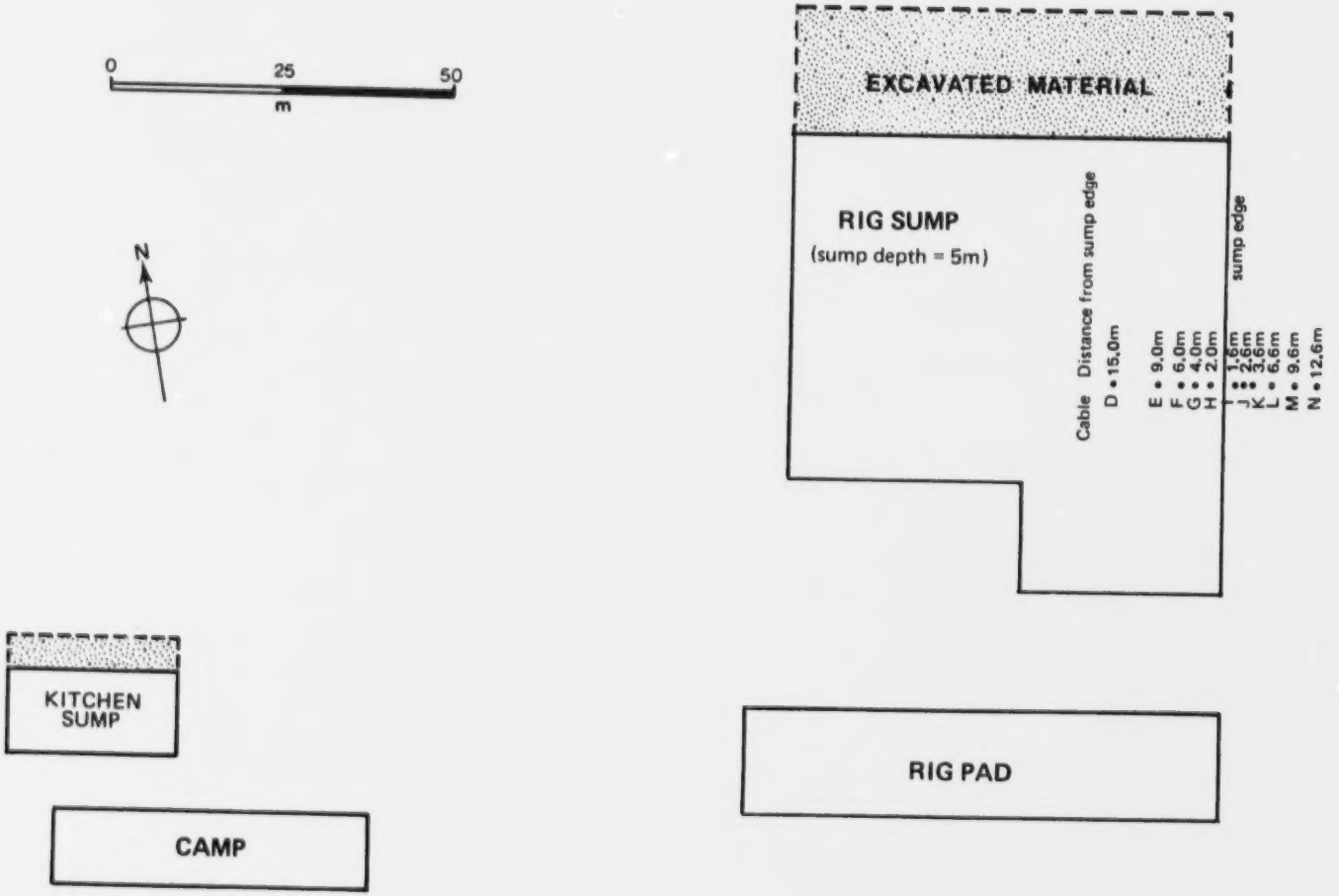


Figure 6. Site layout: Gulf Ogruknang M-31 wellsite.

FIGURE 7 A. Ogruknang M-31 wellsite. General view of the sump under construction, April 2, 1977.

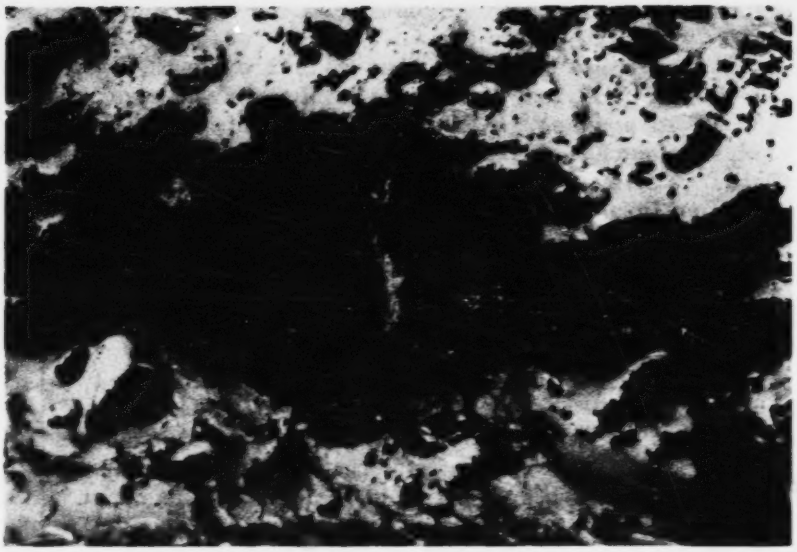


FIGURE 7 B. Ogruknang M-31 wellsite. Small ice wedge exposed in sump wall. Enclosing material is sand and gravel. Massive icy bodies were absent from the walls of the sump although present beneath the sump floor (see Figure 8), April 3, 1977.

FIGURE 7 C. Ogruknang M-31 wellsite. Sampling of drill cuttings from thermistor boreholes for subsequent grain size, bulk density and ground ice determinations, April 3, 1977.

FIGURE 7 D. Ogruknang M-31 wellsite. Completed instrumentation panel for thermistor cables, April 12, 1977.

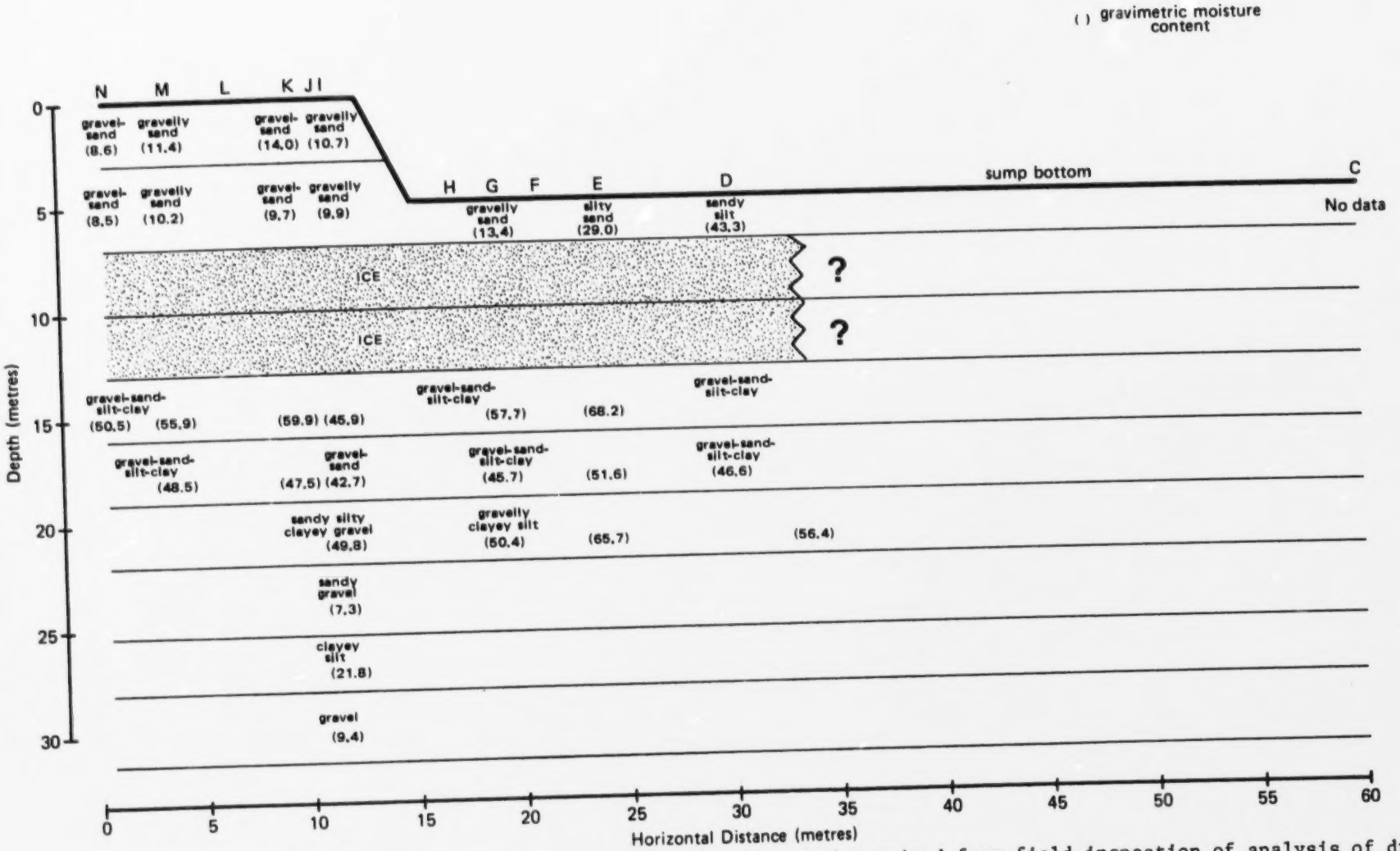


FIGURE 8. Site stratigraphy, Gulf Ogruknang M-31 wellsite, as determined from field inspection of analysis of drill cuttings from boreholes. Note the massive ice body existing at a depth of 2-5 m below the floor of the sump and the generally low ice contents of the materials comprising the sump walls.

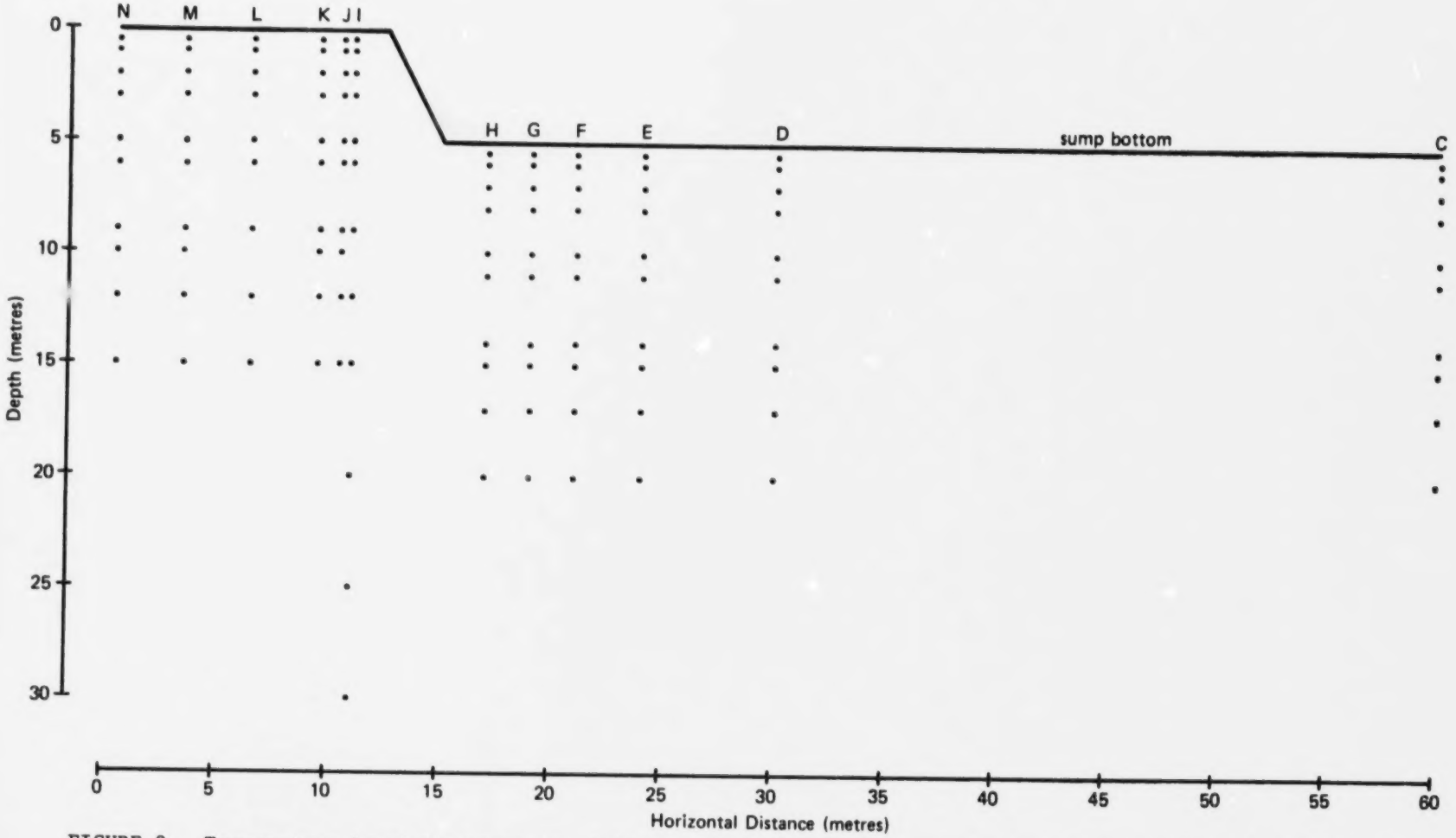


FIGURE 9. Temperature borehole transect, Gulf Ogruknang M-31 wellsite, showing location of boreholes C-N and positioning of YSI thermistors. An additional cable, W, measuring sump floor and fluid temperatures was laid along the floor and wall of the sump. (A similar instrumentation design was established at the Bent Horn 1-01 sump).

In addition, a cable with thermistors at 1 m intervals was draped over the side of the sump and across the sump floor (cable W) to monitor sump fluid temperatures. All boreholes were backfilled with drill cuttings.

At the time of drilling, soil and rock samples were collected for stratigraphic information; these were simply grab samples from drill cuttings. Integrated samples were taken over every 1.5 m (5 feet), so stratigraphic representation should be reasonable. Samples were analysed for moisture content, grain size characteristics and bulk density. These data aid in the interpretation of the ground temperature data, and are required as input into the computer model.

The thermistor cables were led into a central switching panel (Figures 5D and 7D), where temperatures could be conveniently read. The monitoring program was carried out by on-site personnel; readings were taken manually (with a Biddle 72-430 wheatstone bridge) at weekly intervals during drilling, but less frequently thereafter. Because of equipment damage and scheduling problems, the data from Bent Horn are incomplete. There were no serious problems at the Caribou Hills site. Accordingly, the Caribou Hills, M-31 data is presented first in the discussion of results (see Section 6).

5. THE COMPUTER MODEL

A major objective of this phase of the research was to study the pattern of geothermal changes around a sump, and to analyse the problem in terms of heat conduction theory, via computer modelling. Computer simulation not only provides detailed predictions of ground temperature conditions, but also the ability to predict complex and important future or hypothetical events. For example, in the present problem it provided valuable information on temperature conditions in the sump wall, where field instrumentation proved to be difficult. Further the present analysis can be generalised to any sump situation.

The problem is treated as a two-dimensional temperature boundary value problem, with the following additional considerations:

i) the actual geometric configuration (cross-section) must be accommodated;

ii) the site stratigraphic variation must be incorporated;

iii) latent heat effect (phase change) must be included;

iv) the surface boundary conditions vary with space and time (TS = f(x,t)).

Very few closed form mathematical solutions exist for thermal problems involving phase change. The solutions that are available are generally one-dimensional, for simple geometric configurations, uniform material properties and initial conditions, and simple disturbances of boundary temperature. For complex problems, numerical methods must be used. In the present analysis a finite element formulation of the transient heat conduction problem for freezing or thawing soils is used (Hwang et al., 1972). This model has been shown to give satisfactory results in a complex permafrost problem (Smith and Hwang, 1973).

Through the use of the triangular-element grid, any arbitrary geometry can be represented (Figure 10). For the purposes of numerical modelling, the other essential aspects of the real situation were represented as follows:

i) Only half the problem was considered - the other half is assumed to be a mirror-image.

ii) The stratigraphy was represented as a number of horizontal layers.

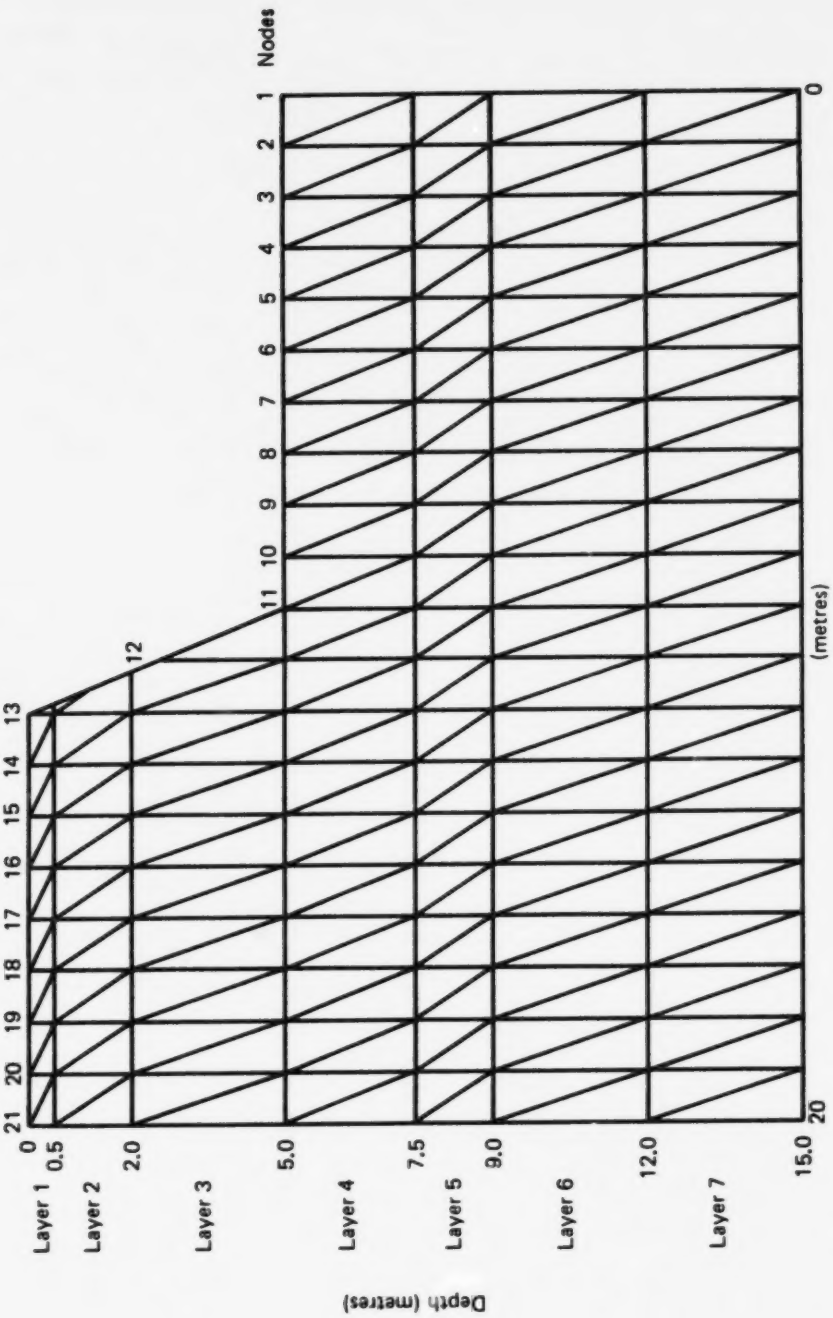
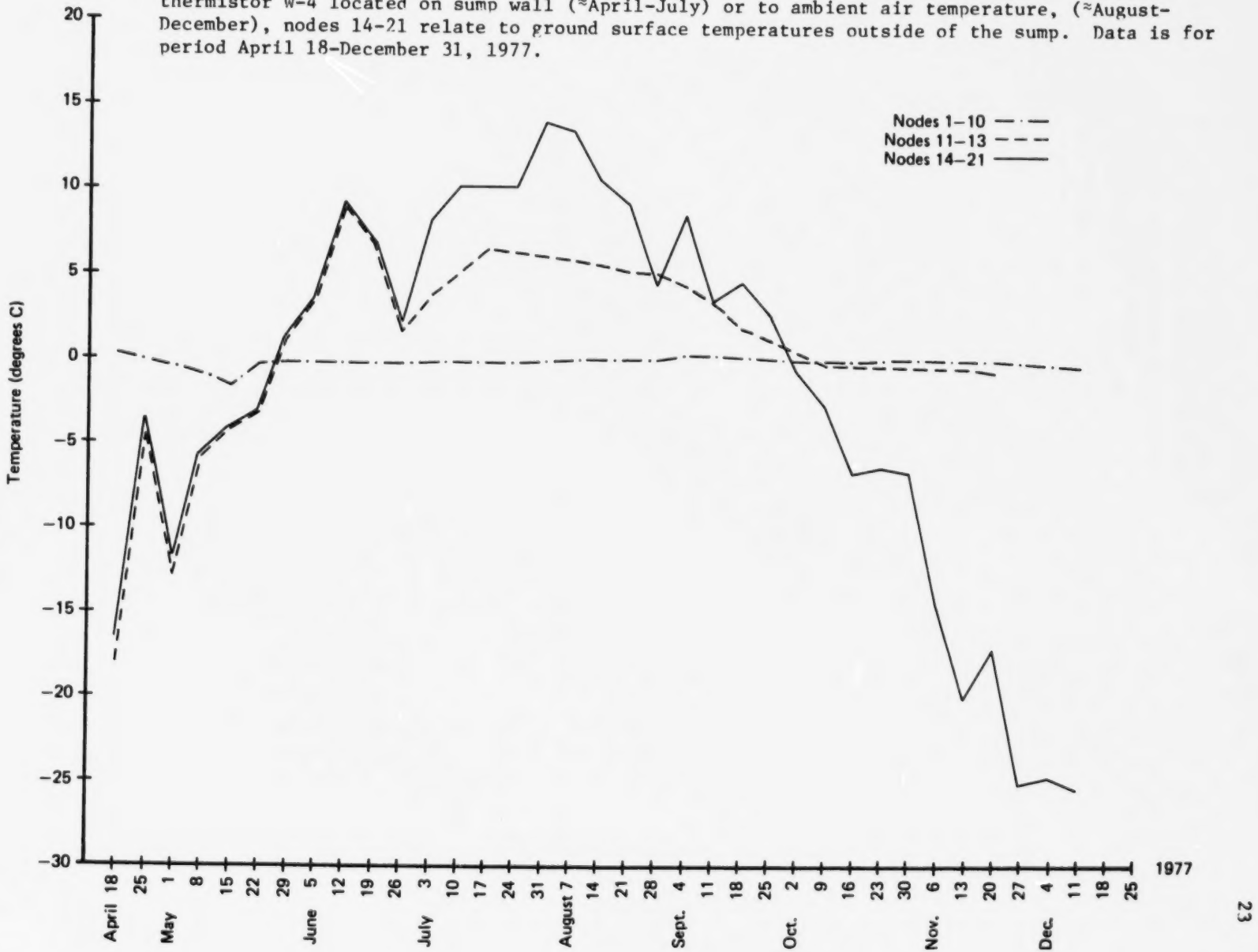


FIGURE 10. Geometry input and finite element layout for the computer model used in the study.

Figure 11. Surface temperature boundary conditions recorded at M-31 and used for sump thermal simulations. Nodes 1-10 relate to thermistor W-10 lying on the sump flood, nodes 11-13 relate either to thermistor W-4 located on sump wall (≈April-July) or to ambient air temperature, (≈August-December), nodes 14-21 relate to ground surface temperatures outside of the sump. Data is for period April 18-December 31, 1977.



iii) Ground thermal properties were not measured directly, but were estimated on the basis of grain-size composition and moisture content according to the method of Johansen (1973). Values for the M-31 site are listed in Table 1.

iv) The ground surface, sump bottom and sump wall were treated as boundaries with temperatures prescribed as following:

a) Nodes 1 to 10 (the sump floor) follow a temperature curve similar to that for thermistor W-10 which was lying on the bottom of the sump (Figure 11).

b) Nodes 11 to 13 (the sump wall) were set either to the sump fluid temperature (thermistor W-4) or the ambient temperature, according to the level of fluid in the sump (Figure 11).

c) At nodes 14 to 21 (the ground surface) temperature varies with the weather and season. Since only air temperature (TA) was available from the site, surface temperatures (TS) were estimated using the computer model described by Smith (1977). This model was used to scale the difference between air and surface temperatures at different times throughout the period, with the following generalised results:

April-May:	TS = TA + 1.5°C
June :	TS = TA + 2°
July :	TS = TA + 1.5°C
August :	TS = TA + 1°
September:	TS = TA
October :	TS = TA - 1°

The surface temperature curve, TS, is also shown in Figure 11.

v) The temperatures at the lower boundary were kept fixed at the values for the initial condition (taken to be the pre disturbance temperature field measured before drilling operations commenced). The left- and right-hand boundaries are assumed to be thermally insulated - i.e., no horizontal temperature gradient and no heat flow across them.

The size of the domain is set by the dimensions of the problem; the resolution of the analytical technique depends on the fineness of the grid that is imposed on this domain. This, in turn, determines the computer requirements of the problem. For the sake of computing

Layer	Interval (m)	Soil Type	Vol. Heat Capacity ($cal/cm^3/C$)		Thermal Conductivity (cal/cm/sec/C)		Vol. Latent Heat (cal/cm^3)
			F	U	F	U	
1	0-0.5	Gravel/ Sand	.25	.30	.0034	.0034	15.8
2	0.5-2.0	Gravel/ Sand	.26	.32	.0050	.0050	17.0
3	2.0-5.0	Gravel/ Sand	.29	.34	.012	.0078	18.9
4	5.0-7.5	Gravelly Sand	.30	.38	.013	.010	22.7
5	7.5-9.0	Mostly Ice	.45	.90	.0059	.0016	63.6
6	9.0-12.0	Mostly Ice	.45	.90	.0060	.0020	62.2
7	12.0-15.0	Gravel-Sand-Silt-Clay	.46	.78	.0071	.0030	47.9

TABLE 1. Ground Thermal Properties, M-31 wellsite, estimated on the basis of grain size, bulk density and moisture content according to the method of Johansen (1973).

efficiency, the grid was made finer in the upper layers where gradients are steeper (Figure 10). Further, the problem was truncated on the left- and right-hand sides where field observations showed no significant horizontal temperature gradient (see (v) above).

The simulation was run for weekly time steps, and for a 21 x 9 grid (20 m by 15 m) over a 38-week period; the program took 10 minutes of CPU time on Carleton University's Xerox Sigma 9 computer. Diagrams of observed and predicted simulated temperatures were also compiled and plotted by computer, using the SYMAP package available at Carleton University (Figures 12-18).

Two other aspects of the thermal problem were analysed using the model described by Smith (1977) and Smith and Tvede (1977). These concerned the details of sump fluid temperatures during freeze back, and the efficacy of insulation materials on sump walls.

6. RESULTS

6.1. Introduction

The geothermal information from the two sites cannot be directly compared since significant differences exist between the two as regards site conditions and the nature of the drilling operations.

The 1-01 wellsite was a one season winter operation while that at M-31 was a two season winter drilling operation (Table 2). The implications of these different operating schedules have already been outlined (French, 1978a, 37-38). In essence, in a one season winter operation, fluids freeze quickly upon entering the sump and infilling is achieved before the fluids thaw during the summer. Sump problems at such sites usually relate to Type A problems or certain Type C problems (Table 3). In the case of the 1-01 wellsite, Type A problems were experienced by the company (French, 1978a, 19-20); the sump was too small to contain all the waste fluids and an additional sump had to be constructed. At periodic intervals during the latter stages of drilling, the frozen fluids were ripped out of the main sump and transported to the auxiliary sump. It is not surprising therefore, that the water cable, W, and several other cables were damaged at 1-01 during operation of the sump.

Two season winter operations generally present more problems than one season winter operations since the sump fluids thaw during the summer when the sump is left open and Type B problems (melt-out of sump walls) may occur. In addition, infilling and site restoration problems (Type C) are more frequent at these localities since the fluids may not freeze during the subsequent winter. Problems encountered at M-31 related to sump infilling.

The nature of site restoration is described in Section 6.5.

Site specific conditions relate to the permafrost characteristics at the two sites. Although both are located in the zone of continuous permafrost, permafrost thicknesses are 720 m at Bent Horn N-72 and 325 m at Ikhil 1-37 in the Caribou Hills (Brown, 1978; Taylor and Judge, 1977). In addition, there are significant differences as regards mean annual ground surface temperatures. These reflect different geologic and permafrost stratigraphies resulting in different ground thermal properties together with latitudinal and climatic variations. Thus, undisturbed permafrost temperatures at 1-01 are considerably cooler than at M-31 (see Sections 4.1 and 4.2). These considerations, when

combined with the varying temperature and chemical composition of the waste drilling fluids entering the sumps, suggest that direct comparison of the geothermal changes recorded is inappropriate. On the other hand, similar general relationships might be expected as regards the disturbance presented by sumps and the overall pattern of geothermal change.

6.2. Accuracy of predictions

The more comprehensive data were obtained from Ogruknang M-31 covering the period April 6, 1977 through to August 1978. Damage to the instrumentation at 1-01 limits the utility of those data.

The predicted patterns of ground temperatures around the M-31 sump for the period May 23 - November 13, 1977, are shown in Figures 12-18. These graphs are derived from computer simulation based upon observed data. It should be pointed out that sharp steps in some isotherms are due to numerical interpolation and the size of the contour interval (up to 5°C in some cases). Temperatures about 0°C are indicated by the symbol 'H'. Sub-zero temperatures are arbitrarily divided into eight classes.

The accuracy of the prediction method is typically exemplified by the data presented in Appendix I (cable G, sump floor and cable K, outside the sump). There is clearly good agreement between observed and predicted values; the maximum error is about 1°C but agreement is typically within ±0.5°C. The consistently warmer predicted values in the middle layers at cable G are undoubtedly due to errors in the specification of ground thermal properties; the conductivities are likely too high. A further error in the model may be the assumption of no unfrozen water in the frozen materials. For cable K agreement is excellent, and the gradual change of geotherm shape over the period is very well reproduced (e.g. compare geotherm B, H, and N). The development of the active layer at K is predicted almost exactly (see geotherms E through L); the maximum depth of about 1.7 m on August 28 is reproduced exactly, and the prediction of freeze-back is also excellent (see geotherms K through O).

6.3. Ogruknang M-31

6.3.1. Geothermal changes

The thermal effect of the sump gradually spreading out into the enclosing permafrost throughout the summer of 1977 is shown in Figures 12-18. These include consideration of the freeze-back period. The actual temperature data recorded is on file with the Environmental Studies Division, IAND, Ottawa.

The most important conclusion to be drawn from the temperature monitoring program is that the thawed zone associated with the sump is

OPERATING PROCEDURES	NUMBER OF WELLSITES VISITED	NUMBER WITH SUMP/OTHER PROBLEMS	EXAMPLES
1. One season winter drilling (Start and finish of operation, including site restoration, within single winter drilling season).	24	4	Hecla 1-69 Drake B-44 Bent Horn 1-01
2. Two season winter drilling (Start and finish drilling within one winter season. Sump left open during summer and site restoration in second winter).	12	6	Parsons Lake N-10 Parsons Lake A-44 Chads Creek B-64 Hecla J-60
3A. Summer drilling (Operation begins in winter and continues into summer. Site restoration in second winter).	7	4	Taglu D-55 Bent Horn A-02
3B. Summer drilling (Operation begins in mid-summer and finishes in following winter).	4	3	Drake D-68 Niglintgak M-19

TABLE 2. Classification of exploratory wellsites examined in 1976 and 1977 according to operating procedures and occurrence of sump and/or other problems.

PROBLEMS	EXAMPLES	COMMENTS
A. Non-containment problems during drilling.	Bent Horn 1-01 Chads Creek B-64 Parsons Lake N-10	Two sumps constructed.
B. Melt-out problems during summer drilling.	Bent Horn A-02 Parsons Lake D-20 Parsons Lake A-44	Undermining of rig. Leakage of fluids. Thermokarst/enlargement of sump.
C. Restoration problems:		
(a) sump infilling and volcano effect	Parsons Lake A-44	Large gravel cap constructed.
(b) sump subsidence and collapse	Drake D-68; Beaverhouse Creek N-13	
(c) lack of infill	Niglintgak M-19; H-30; Taglu D-55	
(d) leakage of fluids	Parsons Lake D-20	
(e) poor geographic locations	Drake B-44; Castel Bay C-68; Hecla J-60; Kumac J-06	
(f) severe terrain disturbance	Bent Horn A-02; Orksut 1-44	

TABLE 3. Analysis of sump problems, with examples documented in text.

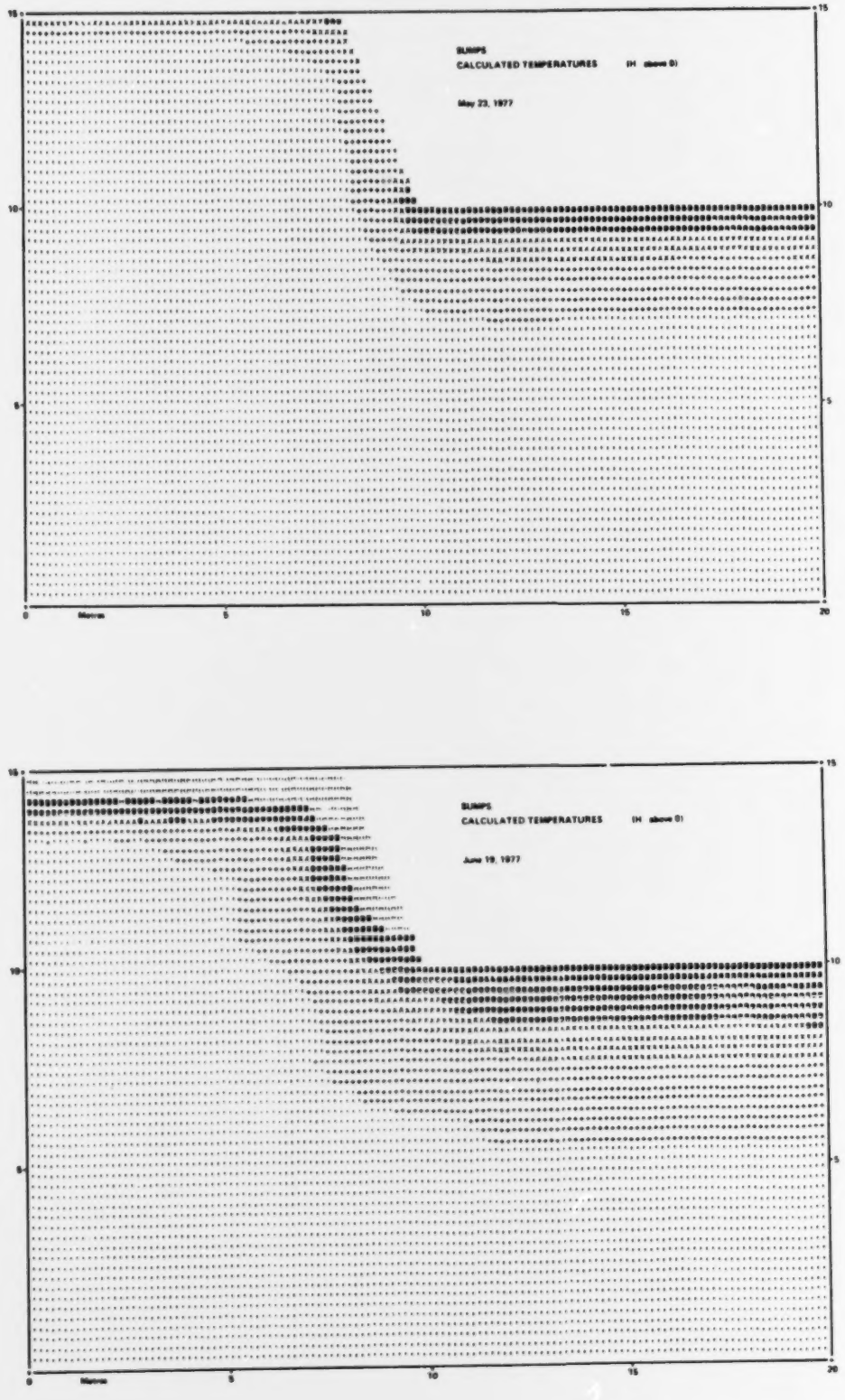


FIGURE 12. Thermal conditions, as predicted from observed data, M-31 sump, May 23, 1977 and June 19, 1977.

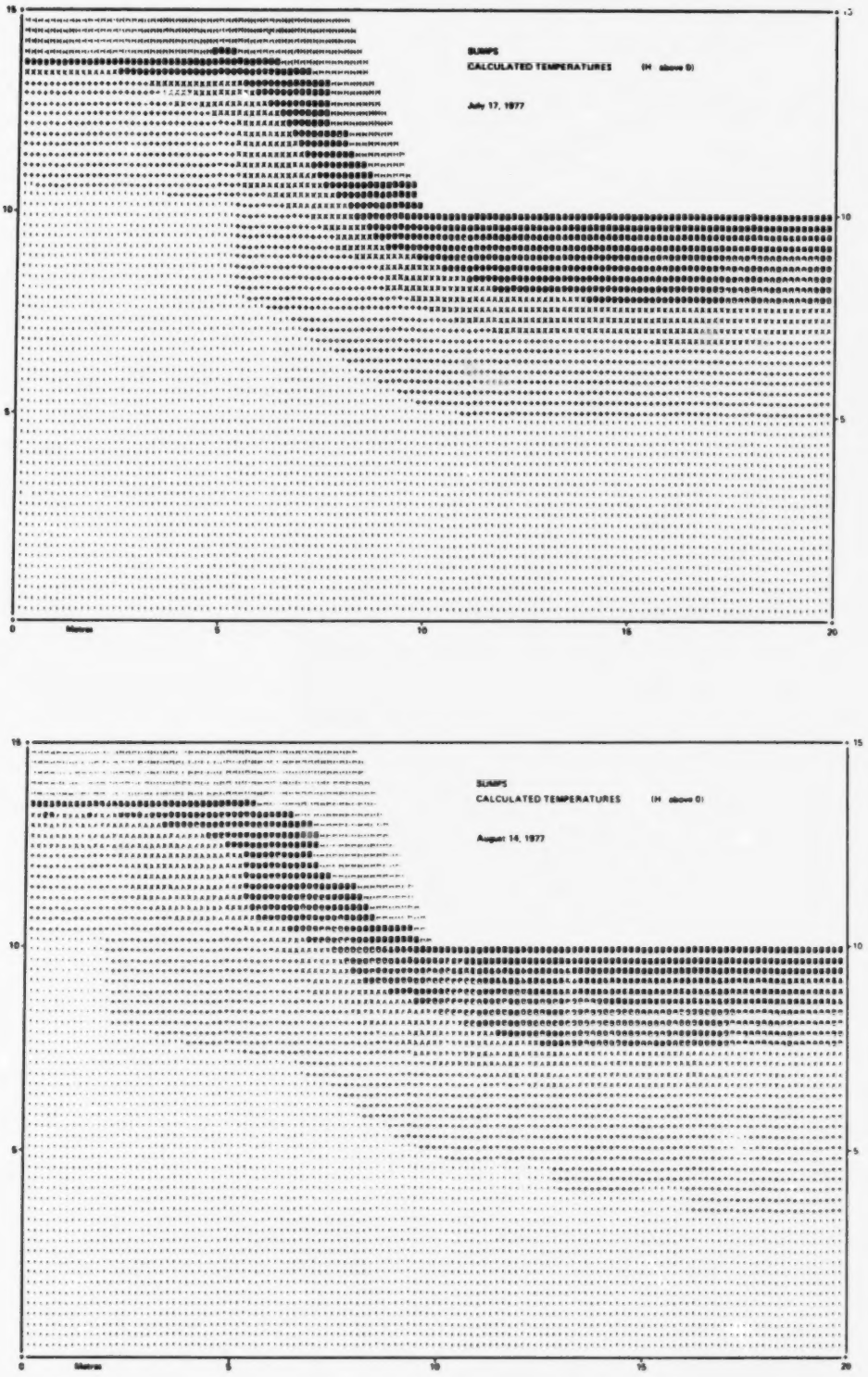
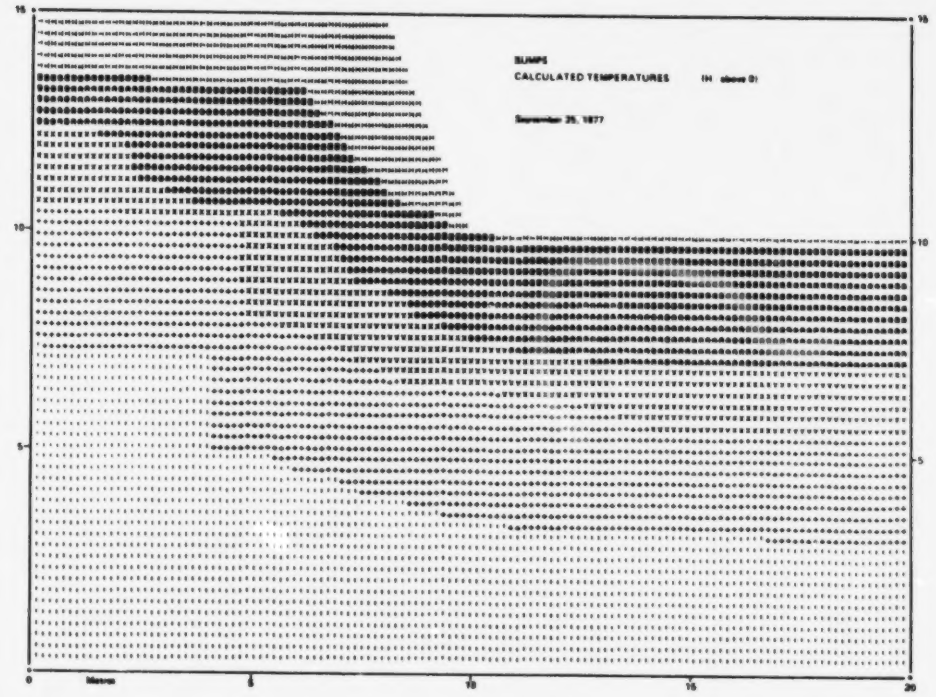


FIGURE 13. Thermal conditions, as predicted from observed data, M-31 sump, July 17, 1977 and August 14, 1977.



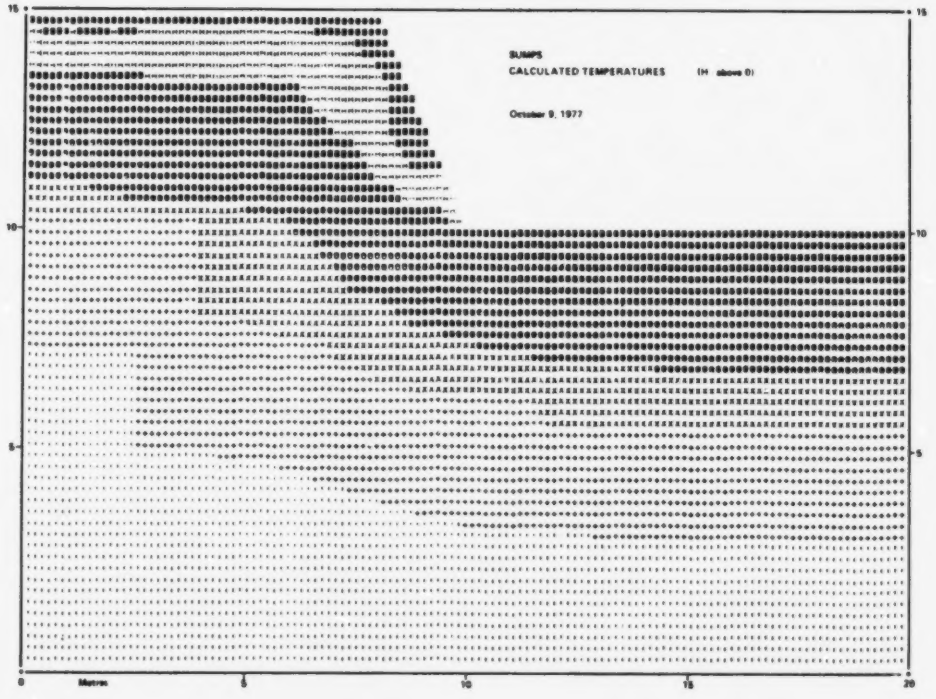


FIGURE 14. Thermal conditions as predicted from observed data, M-31 sump, September 25, 1977 and October 9, 1977.

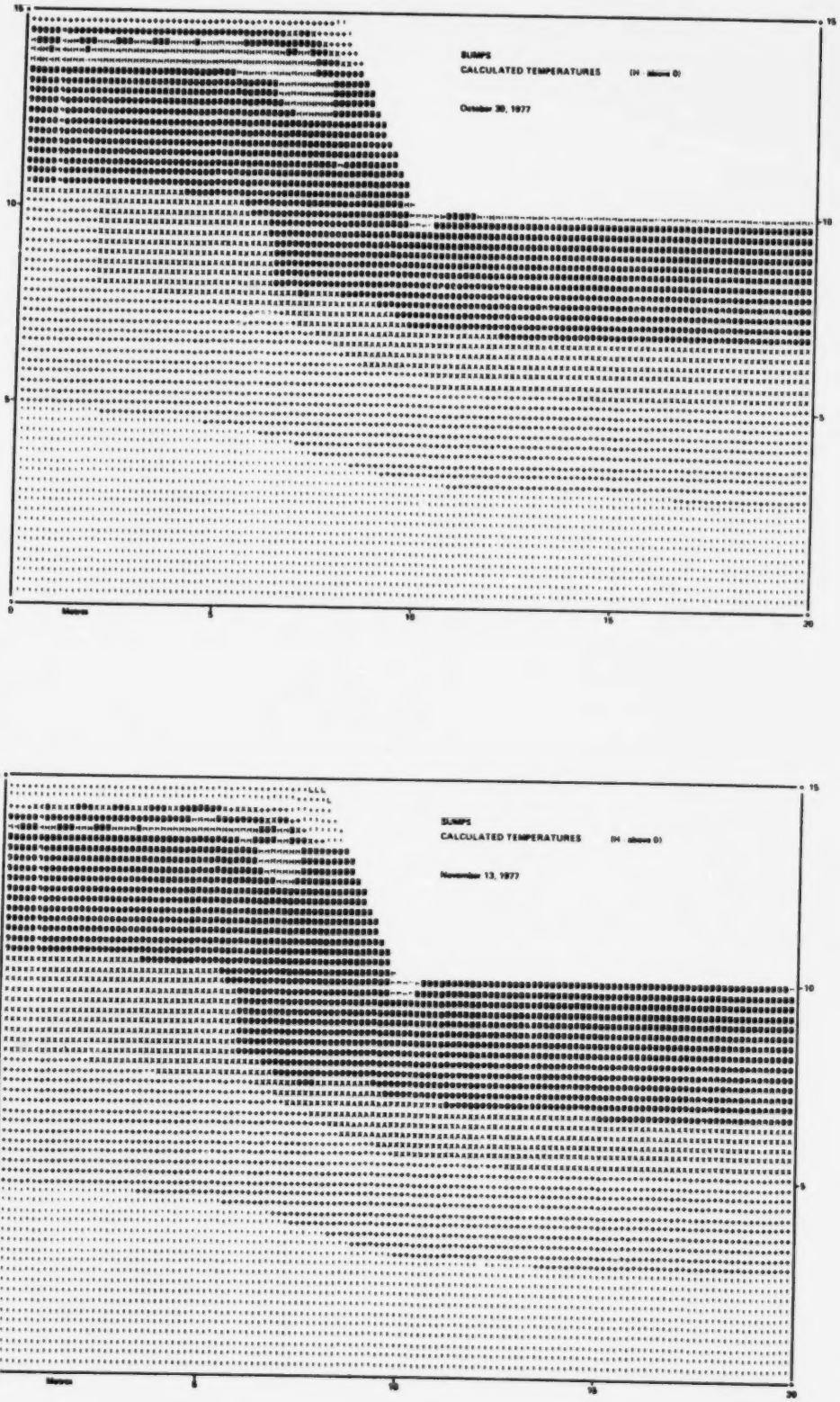


FIGURE 15. Thermal conditions, as predicted from observed data, M-31 sump, October 30, 1977 and November 13, 1977

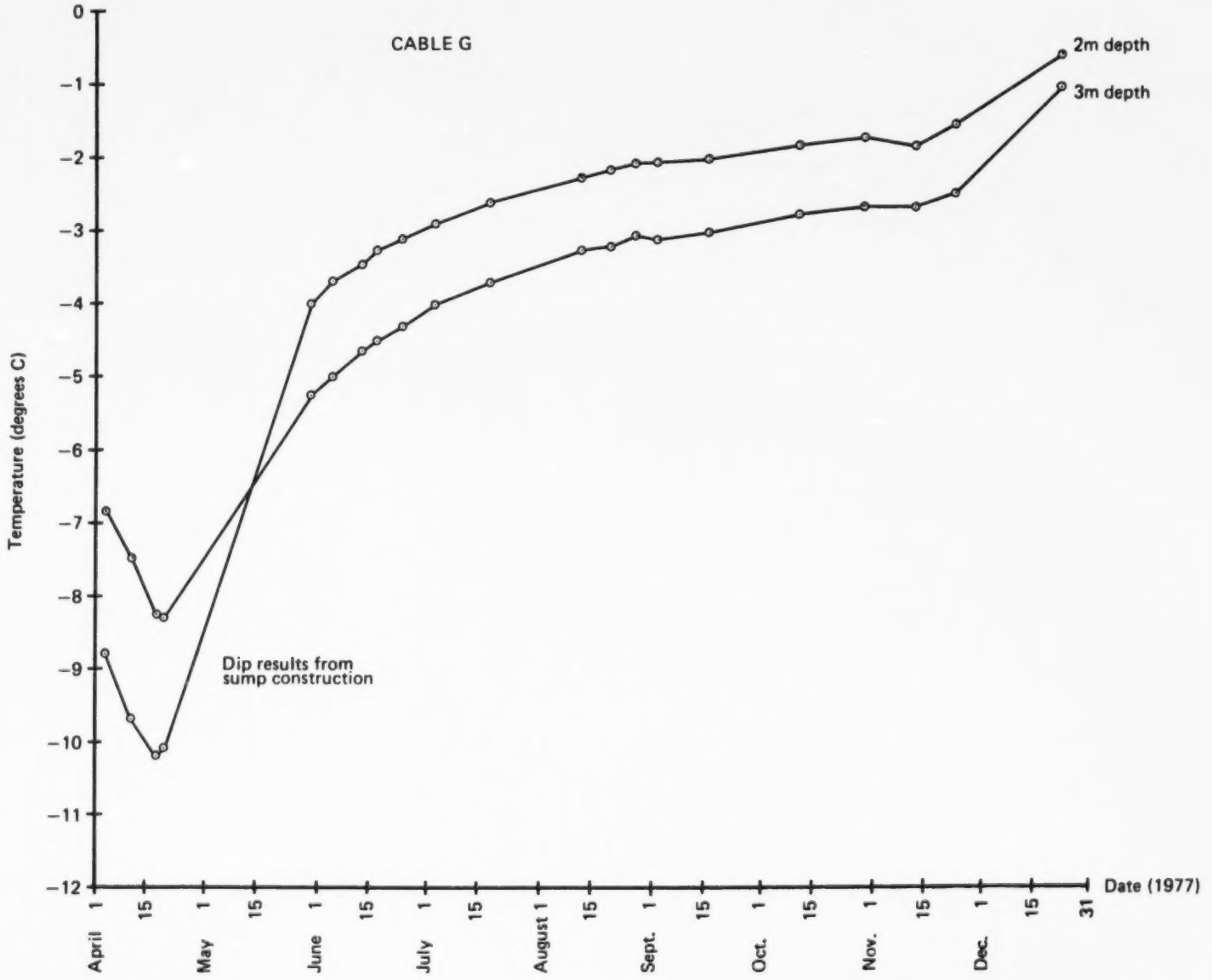


Figure 16. Ground temperatures beneath the sump floor, M-31, as illustrated by data from cable G (see Figure 9 for location of cable G) for period April 4 - December 31, 1977.

confined mainly to the sump walls with virtually no thawing of the sump floor. Sump bottom temperatures however, were modified considerably by the influx of waste drilling fluids. Initially at -15 to -20°C on April 11, 1977, the temperatures of the sump floor warmed up very quickly during the first three weeks of drilling and hovered around 0°C throughout the remainder of the drilling period. On September 2, 1977, after drilling had ceased, the bottom temperatures actually rose to + 0.5°C. The permafrost beneath the sump floor also warmed up quickly at first (from -13°C to -4°C at the 0.5 m depth between April 4 and April 24, 1977) but then more slowly to about -0.5°C by September 16, 1977 (Figure 16). The data show clearly that the sump floor did not thaw during the 1977 summer and the massive ice body located beneath the sump floor (see Figure 8) remained frozen. Since the M-31 operation was a potential worst case situation, the thermal monitoring program supports the contention that thermal degradation during summer beneath an open sump is not extensive.

On the other hand, the significant warming effect of waste drilling fluids upon the permafrost must be stressed. On September 11 for example, the ground temperatures at cable I, nearest to the sump wall, were several degrees warmer than those at comparable depth at cable N, furthest from the sump wall and installed as a control. Maximum sump fluid temperatures recorded during the 1977 summer were in the range + 5°C to + 8°C; by October however, these temperatures had dropped to -1°C (see Figure 21). Figure 19 shows that the warming effect of these sump fluids penetrates to at least 3 m below the sump floor but the thermal monitoring also indicated that, at the 10 m depth beneath the sump floor, temperatures were unaffected. Data obtained in the summer of 1978, a year after cessation of operations, indicate that temperatures at the 2 m depth below the floor of the sump had achieved a quasi-equilibrium of -1.4°C, several degrees warmer than the undisturbed permafrost surrounding the site.

Maximum thaw of the permafrost beneath the M-31 sump was reached in late August 1977 (Figure 15) after which there was little change until freeze-back in early October. Figures 17 and 18 show the active layer freezing back from both top and bottom, the process being virtually complete by mid November. Similar freeze-back patterns are observed elsewhere in the Mackenzie Delta (e.g. Heginbottom, 1973).

Freeze-back of the wall of the sump occurred in early October and is illustrated in Figure 17. There is some uncertainty however, over the precise thermal changes occurring in the sump wall since this prediction is based upon a sump fluid temperature of -0.5°C measured half-way up the sump wall. At this time however, the sump fluid temperature cable (W) showed considerable variation (+1.5°C to -1.5°C). Since drilling had finished in August and presumably, no further fluids

were being put into the sump, it is debatable whether these variations are real or represent error.

In summary, the only significant thaw problems associated with the sump at M-31 were experienced at the sump wall, probably the result of direct and reflected solar radiation. By late August 1977 a maximum of about 2 m of vertical thaw and 2 m of thaw inward from the sump had occurred. If the material comprising the sump wall had been ice-rich, or exposed well-developed ice wedges, melt-out and gullying might have occurred similar to that observed the previous summer at the Bent Horn A-02 and Parsons Lake A-44 sumps (French, 1978a, 18, 27-28).

6.3.2 Use of insulation

Urethane insulation has been used at various locations in the past to protect sump walls from thaw, but little is known about the effectiveness of this procedure. The efficacy of this measure was examined via computer simulation. A control run, with the natural situation, predicted 1.9 m of thaw in the sump wall (a value in excellent agreement with that inferred from temperature observations at M-31 - see above, Section 6.3.1.). A second simulation was run with a 10 cm layer of urethane on the surface; the predicted thaw was about 1.7 m (Figure 20), a reduction of only approximately 10%. This suggests that the use of insulation matting placed over the sump walls and dykes is not a highly effective measure.

This conclusion seems to be borne out in certain field reports, especially those concerning the Mackenzie Delta.

6.3.3. Freeze-back of sump fluids

The nature and rate of freeze-back of sump fluids is of particular concern since the rationale for sump use is that waste drilling fluids freeze in situ in the enclosing permafrost. In this manner permanent containment is achieved and toxicity effects, if any, are minimised. In many instances however, particularly at localities where the sump is left open during the summer, there is evidence that the waste fluids in the sump are not completely frozen at the time of infill. Often, the weight of the overburden has led to collapse of the frozen sump surface and an upwelling of fluids to the surface (the volcano effect). Part of the problem may relate to the salt content of the waste fluids which

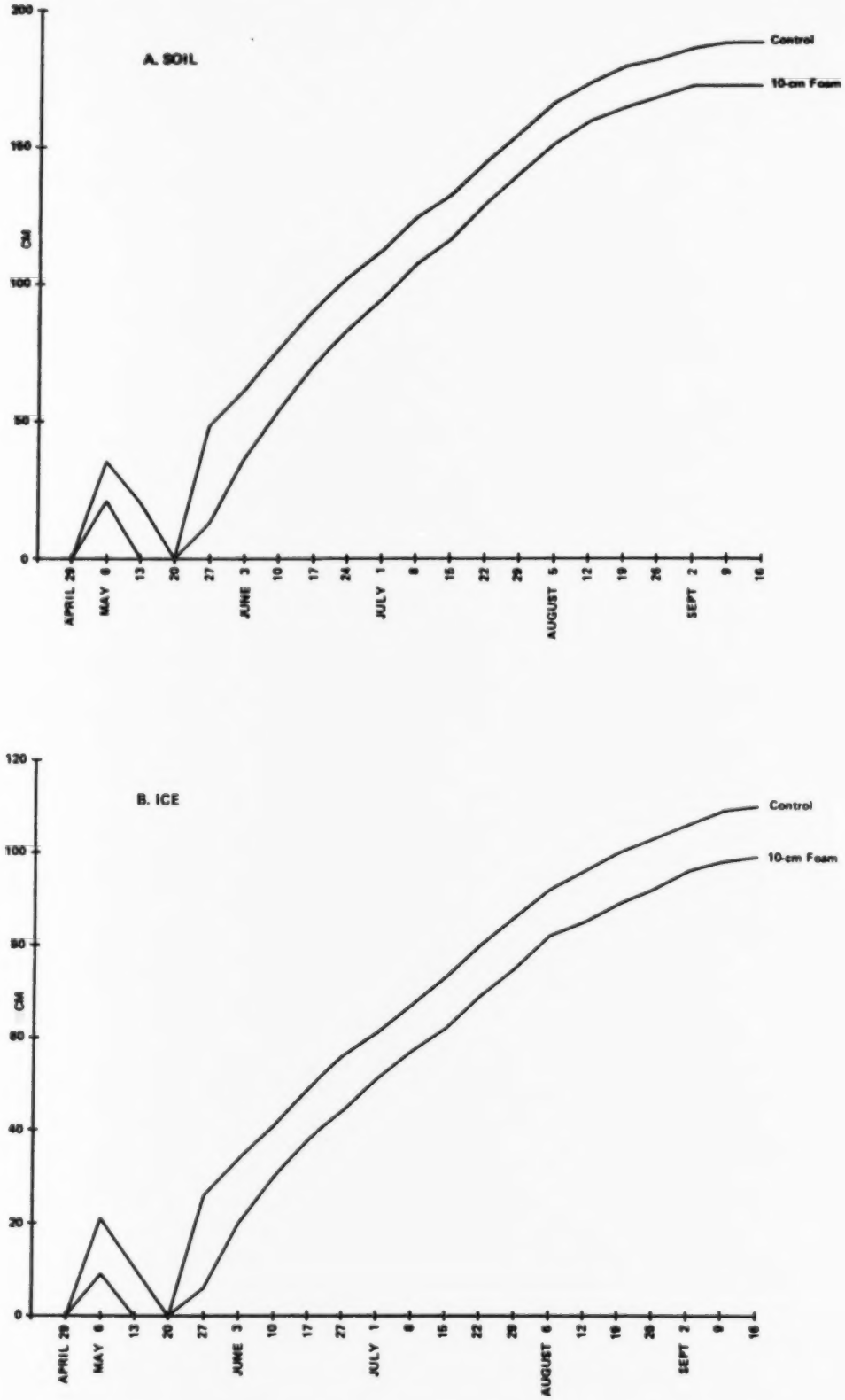


FIGURE 17. Simulation of the effect of a 10 cm thick urethane foam insulation on thaw of (a) mineral soil and (b) ice.

lowers the freezing point. One objective of the thermal monitoring program was to obtain information upon the rate of freeze-back of sump fluids.

At M-31 the sump fluids thawed completely during the summer of 1977 and temperatures as high as + 8°C were recorded in early August. By the beginning of October, in response to falling air temperatures, fluid temperatures at the surface had fallen to -1°C and in all probability the surface started to freeze then or shortly afterwards.

The temperatures recorded in the sump fluids during the period from September 1977 until February 1978, at which time the sump was infilled, are presented in Figures 21, 22, and 23. The data indicate that only the upper 2.0 m of fluid dropped below 0°C by mid February. Assuming freezing occurred at 0°C, a maximum of 2 m of ice had formed within the sump at that time, and the deeper sections of the sump were unfrozen. As might be expected therefore, the sump 'broke' during the infilling operation and unfrozen waste drilling fluids escaped to the surface (see Section 6.5.).

The monitoring program was of insufficient duration to ascertain the rate of eventual freeze-back of these fluids. In addition, chemical analyses of the sump fluids were required to determine the freezing point, and these were not undertaken in this study. However, it seems clear that, once sump fluids are allowed to thaw, as happens during a two season winter drilling operation, the fluids will not refreeze any more deeply or quickly than adjacent natural water bodies. In the Mackenzie Delta, there is abundant evidence to indicate that water bodies in excess of 2-3 m in depth do not freeze to their bottoms in winter and, in fact, may promote the development of substantial thaw zones or taliks (e.g. Johnston and Brown, 1964; Smith and Hwang, 1973).

At M-31 several factors suggest that the sump fluids eventually freeze rather than promote thermal degradation. First, by late August 1978, ground temperatures immediately beneath the sump had achieved a quasi-equilibrium of -1.4°C. No summer rise in temperatures, related to the thaw of the fluids, was discernible at that depth. Second, the sump fluids became intermixed with the frozen overburden at the time of infilling in February 1978 and any thermal effects associated with the unfrozen fluids would have been dissipated. It follows that consideration should be given to the construction of shallow sumps at localities where the sump fluids will be allowed to thaw since such a configuration will freeze more completely during the following winter.

6.4. Bent Horn 1-01

6.4.1. Introduction

Since this was the first sump ever instrumented, problems were encountered which make the results less comprehensive than one might

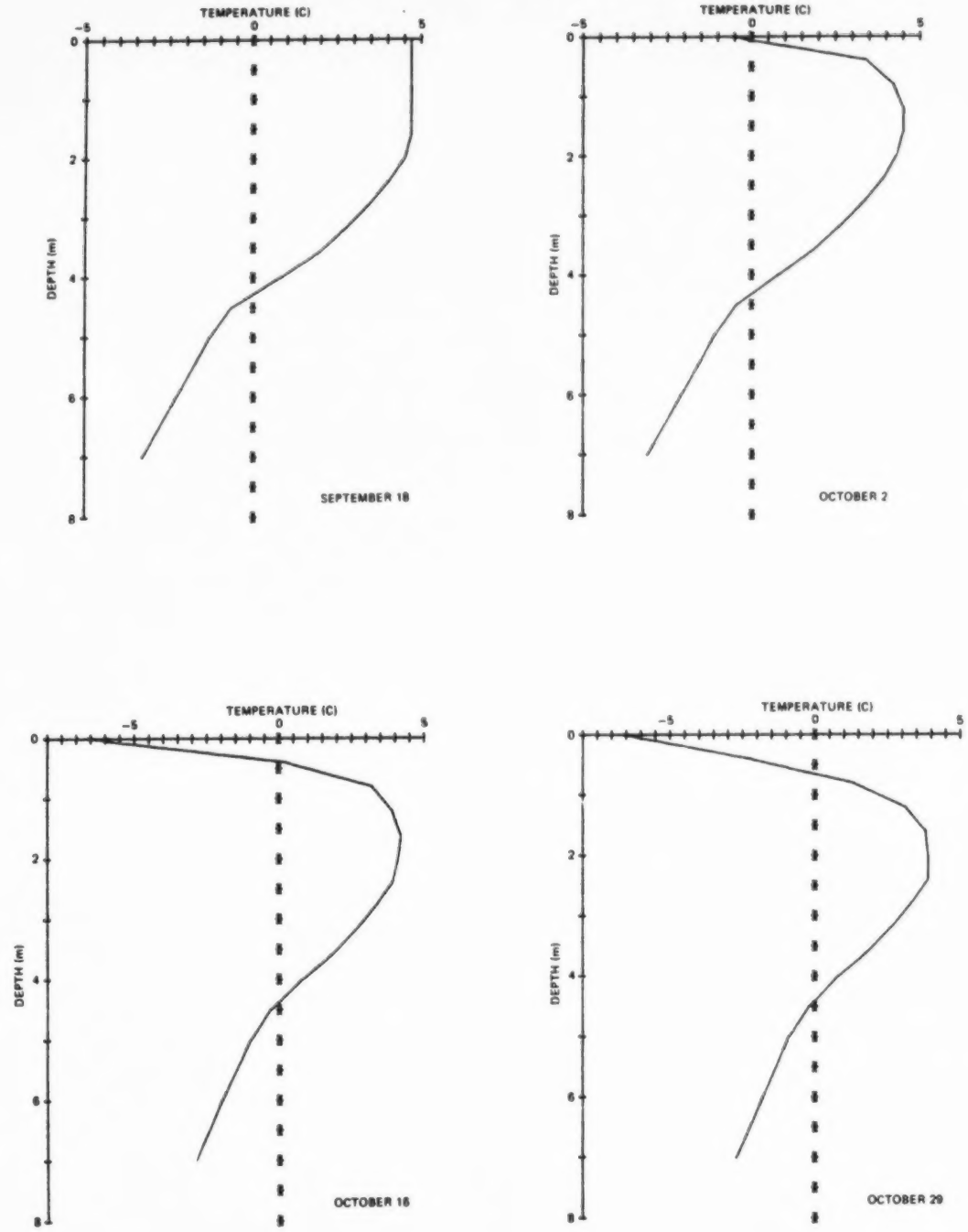


FIGURE 18. Sump fluid temperatures, M-31, September 18 - October 29, 1977.

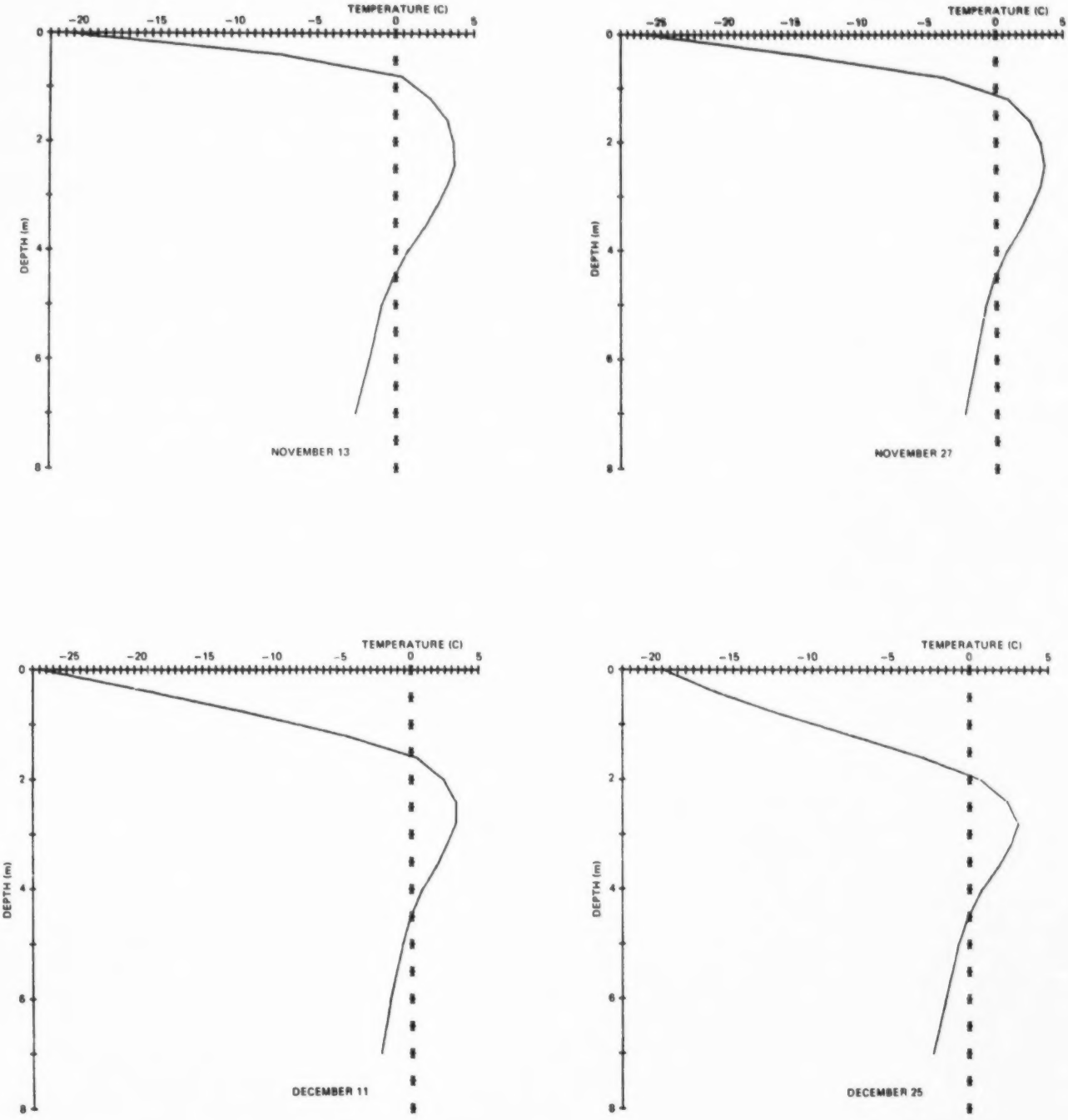


FIGURE 19. Sump fluid temperatures, M-31, November 13 - December 25, 1977.

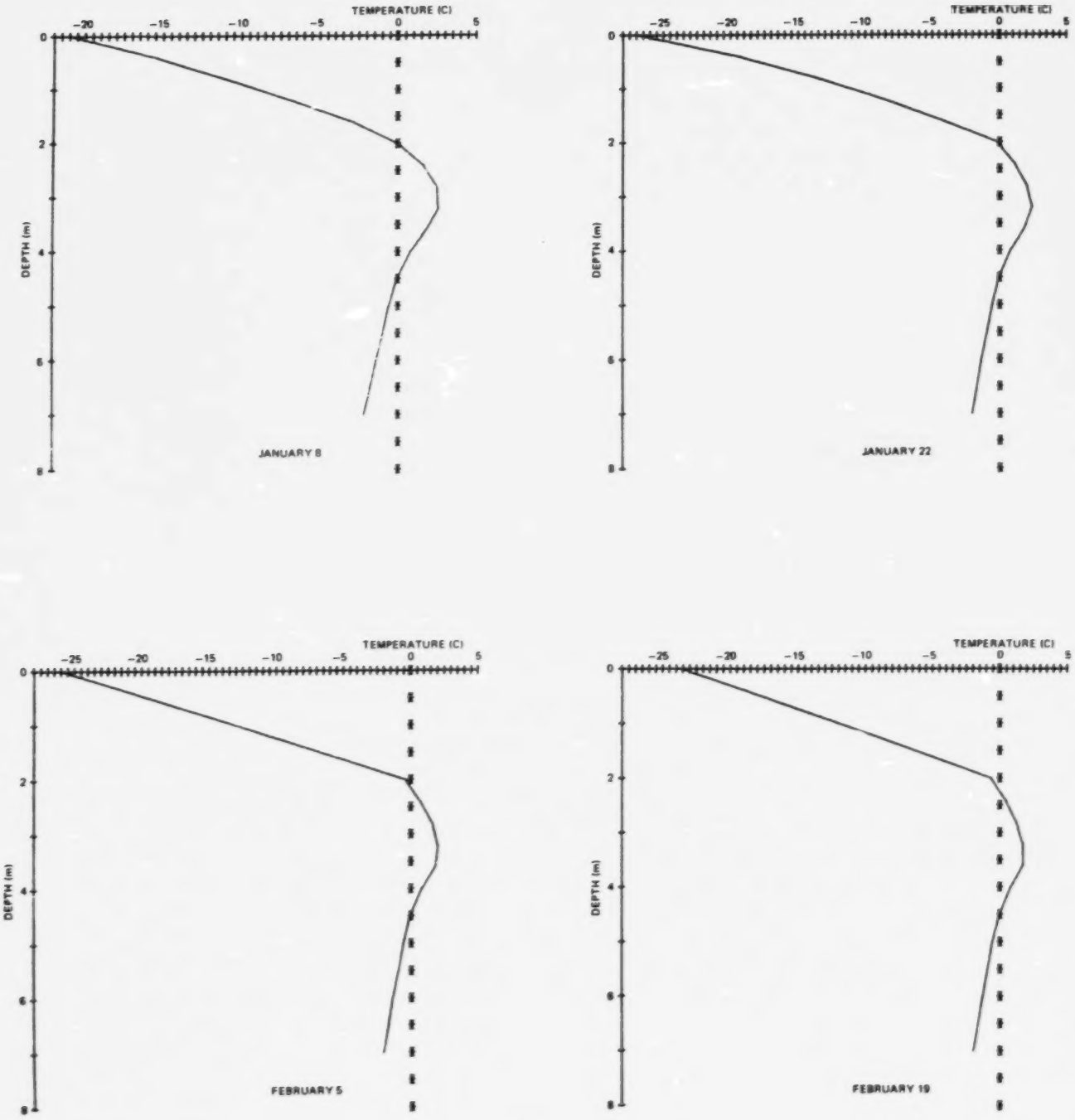


FIGURE 20. Sump fluid temperatures, M-31, January 8 - February 19, 1978. Infilling of the sump commenced February 20, 1978 (see Figures 21 C and 21 D).

wish for. Upon analysis, it is clear that, although more instrumentation than was necessary was installed in November 1976, some of the potentially most useful information was lost at an early stage due to damage. This included the loss of the cables to measure the sump fluid and the sump floor temperatures. Further cables were damaged later during the drilling period presumably when frozen fluids were periodically removed from the sump, and also at the time of sump infill in May 1977. In August 1978, only 5 cables remained operational (Figure 21A).

6.4.2 Geothermal changes

Data collected from the 1-01 site support the general trends observed more systematically at the M-31 site. A major difference, however, is the fact that the 1-01 well was a one season winter drilling operation. It turns out that the geothermal effects of sumps operated in winter in the high Arctic will cause no melting of the permafrost since the fluids must freeze virtually instantaneously.

Undisturbed permafrost ground surface temperatures in the Bent Horn area are between -15 and -20°C. These values are based upon the temperature logging of the adjacent Bent Horn N-72 wellsite (Taylor and Judge, 1977). At 1-01 the first temperature readings were taken on December 19, 1976, approximately one week after commencement of drilling. At the time the sump floor temperature had already risen to -10.6°C. Shortly after this the cable was damaged. Repairs were attempted but were unsuccessful due to the winter weather conditions. The next data were obtained on May 5, 1977, when repairs were possible. On that date the sump floor temperature was -9.1°C and the temperature of the sump fluids themselves was -8.8°C. It seems safe to assume therefore, that the sump fluids remained frozen throughout this period. Moreover, since infilling of the sump took place shortly afterwards, there was little opportunity for the fluids to thaw before burial. Unfortunately, the cables were again damaged at the time of sump infilling. No further temperature data are available therefore, to support the conclusion that the sump fluids have remained frozen but field visits in August 1977 and August 1978 did not reveal any visible signs of thawing and subsidence of the sump.

As at M-31, the considerable warming effect of the sump fluids upon the enclosing permafrost must be stressed. For example, at cable B (see Figure 4) the temperature at the 0.25 m depth beneath the sump floor was between 10 - 12°C warmer than at a comparable depth at cable G in early May 1977. This warming effect vanishes at the 5.0 m depth below the sump, thus confirming the data obtained from M-31 with respect to thaw penetration below the sump floor.

FIGURE 21 A. Bent Horn 1-01, August 21, 1978. Oblique air view of restored site. Note the open flare pit filled with water but no slumping of the sump overburden.

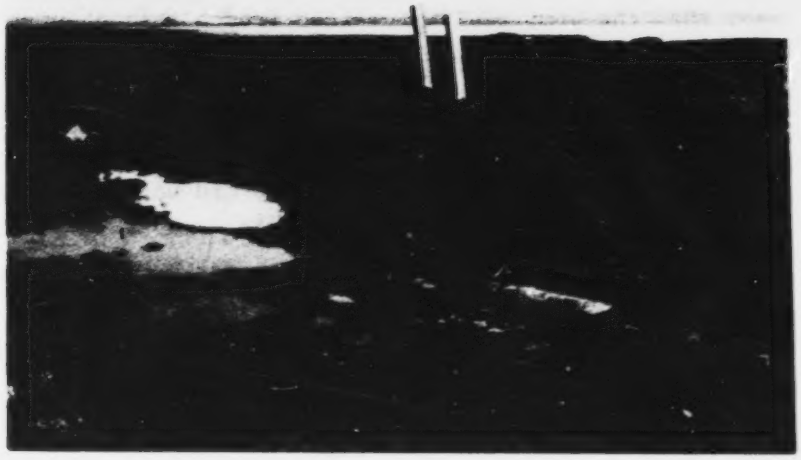


FIGURE 21 B. Bent Horn 1-01, August 21, 1978. Remains of instrumentation panel and thermistor cables; only 5 out of 13 cables were still functioning. Surface of the sump was dry and compacted.

FIGURE 21 C. Ogruknang M-3I, March 2, I978. View of sump in early stages of infill. Material in background is being pushed into sump. Note the snow within the sump.

FIGURE 21 D.
Ogruknang M-3I, March I0, I978. View of sump in middle stages of infill. The weight of the overburden is causing an upwelling of unfrozen sump fluids and cracking of frozen sump surface. Soon after, the sump 'broke'. (see Figure 3C for restored site photograph, August 4, I978).

The limited nature of the thermal data obtained from the 1-01 wellsite is of insufficient quality to allow interpretation of geothermal changes or the generation of computer predictions, as undertaken for M-31.

6.5 Site restoration problems, Bent Horn 1-01 and Ogruknang M-31

Site restoration problems of different types were experienced at each wellsite.

At Bent Horn 1-01 problems related to the insufficient capacity of the sump and the necessity to construct an additional sump during drilling. When infilling of the main sump took place in May 1977, it was very full. In addition, frozen lumps of waste drilling fluids were scattered around the sump as a result of the periodic removal of frozen fluids to the auxiliary sump, 0.4 km distant, during the later stages of drilling. Inevitably, these became incorporated in the overburden during infilling. By August 1977, the surface of the sump was waterlogged and waste fluids mixed in with the overburden were visible at the surface (see French, 1978a, Figure 7a). In August 1978 however, the sump had compacted well and the excess water had drained away or evaporated (Figure 24B). No signs of thawing or subsidence of the sump were visible and it seems highly probable that the sump fluids have remained frozen.

Restoration problems at M-31 were associated with sump infilling. The weight of the overburden caused the frozen sump surface to break (Figures 21C, 21D) and the upwelling of the unfrozen fluids beneath to occur. There fluids were eventually contained. The method used was that of progressive encroachment of gravel placed around the sump (see Figure 3C). Although some of the fluids may now be contained above the ground surface (i.e. within the gravel cap) these will probably freeze in time. Inspection of the site for possible leakage of fluids should be undertaken during the summer of 1979.

7. SUMMARY

7.1. Sump geothermal disturbances

The following conclusions are drawn from the study:

1) The use of sumps to contain waste drilling fluids at the two wellsites monitored does not lead to significant permafrost degradation beneath the sumps.

2) The influx of waste drilling fluids into the sumps causes significant warming of the upper 1.0 - 2.0 m of the permafrost below the sump floor. Temperature rises may be in the 5 - 10°C range. At depths of 5.0 - 10.0 m below the floor of the sumps the warming effects disappear.

3) In a one season winter operation (Bent Horn 1-01) permafrost temperatures at the 0.25 m depth below the floor of the sump rose from between -15 and -20°C before commencement of drilling to -9°C during drilling. Temperatures of the frozen sump fluids at the end of drilling were -8°C. Since sump infilling took place before summer thaw, it seems reasonable to suppose that the fluids have remained frozen.

4) In a two season winter operation in which the sump fluids were allowed to thaw during the summer (Ogruknang M-31) the following geothermal conditions were observed:

   a) During the first three weeks of operation, temperatures at a depth of 1.0 m below the floor of the sump rose by 3 - 4°C to -4°C and then more slowly to a quasi-equilibrium of between -1 and -2°C over the following twelve months.

   b) Temperatures on the floor of the sump rose to + 0.5°C during late summer.

   c) Minimal thawing of the sump floor took place during the summer but thawing to a depth of 2.0 m occurred on the sump walls.

   d) The sump fluids were not completely frozen at the time of sump infilling in the February of the following year, and led to restoration problems.

5) In areas of warmer permafrost temperatures the geothermal disturbance created by an influx of sump fluids may be sufficient to induce thermal degradation of the sump floor.

6) In areas which experience higher mean summer air temperatures the presence of an open sump, probably in combination with warm permafrost temperatures and high ground ice amounts, may lead to substantial melt-out problems not encountered in this study.

7) Accurate numerical simulation of geothermal disturbances associated with sumps is possible, given information upon air temperatures, average ground surface temperatures and estimates of ground thermal properties. Variations in temperature of the fluids entering the sump and the temperature at which the fluids freeze will also determine the direction and the rate of geothermal change.

7.2. Implications for Arctic Land Use Regulations

The following recommendations relate only to the terrain and geothermal aspects of sumps in permafrost:

1) The major terrain problems associated with sumps in areas of relatively cold permafrost, as existing at the two sites monitored, appear related not to geothermal disturbances leading to the non-freezing of sump fluids and/or the melt-out of sumps but to restoration procedures and techniques.

2) At every operating rig there is a need for a flare pit, a camp waste sump and a drilling waste sump. They should all be as small as possible to minimise terrain disturbance, particularly if the underlying sediments are prone to thermokarst development and gullying. The destruction of the surface organic mat should be prevented wherever possible.

3) One method to ensure a small drilling waste sump is to allow for decanting of fluids during drilling operations. If the fluids are non toxic or can be treated (e.g. by charcoal filtering) direct disposal can proceed either into a water body or upon land. It is recognised that treatment and disposal of fluids during drilling is often impractical in the Arctic due to the freezing of sump fluids in winter, and that this process appears best suited to summer operations.

4) If sump fluids are toxic and are not subject to treatment, containment of fluids is recommended. This can be accomplished by the use of a sump sufficiently large to contain all waste fluids, as required under present Land Use Regulations. An alternative is to consider the identification of designated disposal sites, to which fluids can be trucked. The latter is thought to be especially applicable to exploratory operations in the Mackenzie Delta and to developmental sites where a number of wells exist in close proximity to each other.

5) The methods of decanting of small sumps would vary temporally. During winter, the frozen fluids can be ripped and trucked to disposal sites which may be old borrow pits or areas of no vegetation. During summer, pumping of the supernatant water is possible.

6) Recommended restoration procedures vary temporarily. During winter, infilling as under present Land Use Regulations has the advantages of minimal terrain disturbance but the disadvantages of poor infilling and compaction together with the extra costs of blasting the frozen infill. Infilling during the summer presents the problem of substantial terrain disturbance. However, better infilling is achieved with thawed material and this might be most effective in association with summer decanting of the supernatant fluids. Restriction of vehicle movement to the immediate lease, and the use of gravel pads or matting wherever possible are essential for this option. Under these conditions, decanting and infilling might be sanctioned immediately after completion of drilling; the optimum time for summer infilling is immediately after freeze-up and before the stockpiled fill becomes frozen and required blasting.

7) Present Land Use Regulations with respect to sumps appear inflexible. We recognise geographic and seasonal variability.

   a) Geographic variability. From a purely utilitarian viewpoint we distinguish at least 4 terrain environments: (i) polar deserts, e.g. most of Prince Patrick Island, (ii) High Arctic tundra 'oases', e.g. southwest Cameron Island, (iii) the Modern Mackenzie Delta, and (iv) the Pleistocene Mackenzie Delta.

      These environments are not comprehensive of the wide range present in Canada's Arctic, but reflect those examined in this project to date. While categories iii and iv are site specific, categories i and ii are pedological in nature.

      We recommend that no sumps are necessary in areas of polar desert soils. In tundra oases either present land use procedures should be continued or a small sump used in association with decanting procedures. In the Modern Mackenzie Delta where annual flooding occurs sumps are not necessary since there is a natural flushing mechanism. In the Pleistocene Delta, we recommend either the use of natural disposal sites (borrow pits, enclosed lakes without fish, etc.) or a small sump associated with decanting procedures, or a large sump and total containment of fluids as under present Land Use Regulations.

   b) Seasonal variability. We recognise that procedures may vary according to time of year (see points 5 and 6 above). Where operations span both summer and winter, it may be necessary to plan for changes in land use procedures during the operation, such as the provision of both winter and summer roads for decanting and trucking disposal.

8. REFERENCES

Argument, R.T. 1973. Specifications for sump construction in the Mackenzie Delta. Shell Canada Limited, Production Department, Drilling Division, Calgary, 9 p.

Brown, R.J.E. 1978. Permafrost. In: Hydrologic Atlas of Canada. Environment Canada, Ottawa. Plate 32, map and explanatory notes.

French, H.M. 1978a. Sump studies I: Terrain disturbances. Environmental Studies No 6, Indian Affairs and Northern Development, Ottawa, 52 p.

-------- 1978b. Terrain and environmental problems of Canadian Arctic oil and gas exploration. Musk-Ox, 21, 11-17.

Heginbottom, J.A. 1973. Effects of surface disturbance upon permafrost. Report 73-16, Environmental-Social Committee Northern Pipelines, Task Force on Northern Oil Development, Information Canada, 29 p.

Hwang, C.T., D.W. Murray and E.W. Brooker, 1972. A thermal analysis for structures on permafrost. Canadian Geotechnical Journal, 9, 33-46.

Johansen, S.O. 1972. Beregningsmetode for varmeledningsevne av fuktige og frosne jordarter (A method for calculation of thermal conductivity of soils, Part II). (With English summary). Frost I Jord, 10, 13-28.

Johnston, G.H. and R.J.E. Brown, 1964. Some observations on permafrost distribution at a lake in the Mackenzie Delta. Arctic, 17, 162-175.

Judge, A.S. 1973. The prediction of permafrost thickness. Canadian Geotechnical Journal, 10, 1-11.

Mackay, J.R. 1974. Seismic shot holes and ground temperatures, Mackenzie Delta area, Northwest Territories. Geological Survey of Canada, Paper 74-1A, 389-390.

Smith, M.W. 1977. Computer simulation of microclimatic and ground thermal regimes; test results and computer description. Ottawa, Indian and Northern Affairs, ALUR 75-76-72, 74 p.

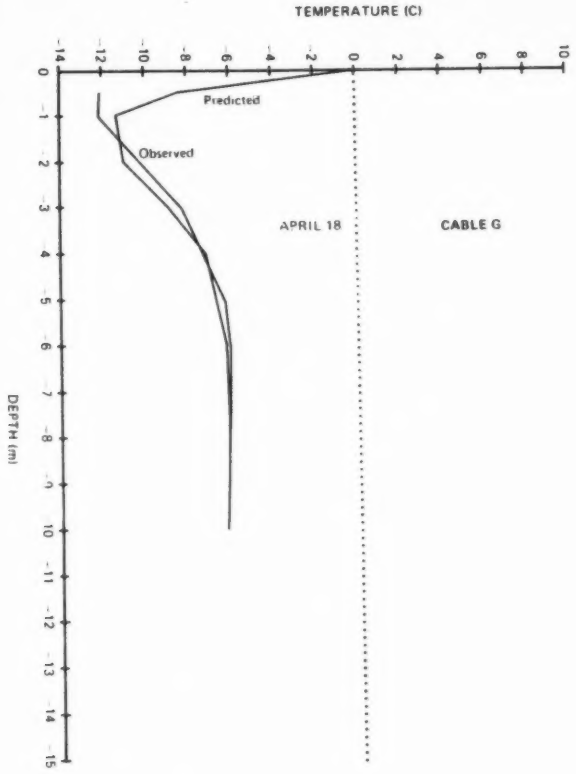
-------- and C.T. Hwang, 1973. Thermal disturbances due to channel shifting, Mackenzie Delta, N.W.T., Canada. In: Permafrost; North American Contribution, Second International Permafrost Conference, Yakutsk, U.S.S.R. National Academy of Sciences Publication 2115, Washington, D.C., 135-155.

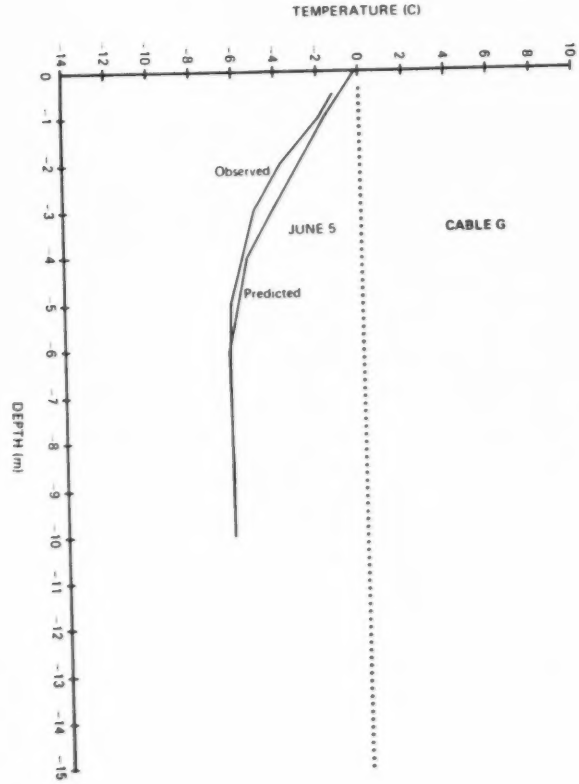
-------- and A. Tvede, 1977. The computer simulation of frost penetration beneath highways. Canadian Geotechnical Journal, 14, 167-179.

Taylor, A.E. and A.S. Judge, 1977. Canadian geothermal data collection - northern wells, 1976-1977. Geothermal series No 10, Geothermal Service of Canada, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, 194 p.

Tedrow, J.C.F. 1977. Soils of the Polar Landscape. Published by Rutgers University Press, New Jersey. 638 pages.

APPENDIX I. Observed and predicted geotherms at cables G and K, Gulf Ogruknang M-31 wellsite, Caribou Hills.


TEMPERATURE (C)
DEPTH (m)
Predicted
Observed
APRIL 18
CABLE G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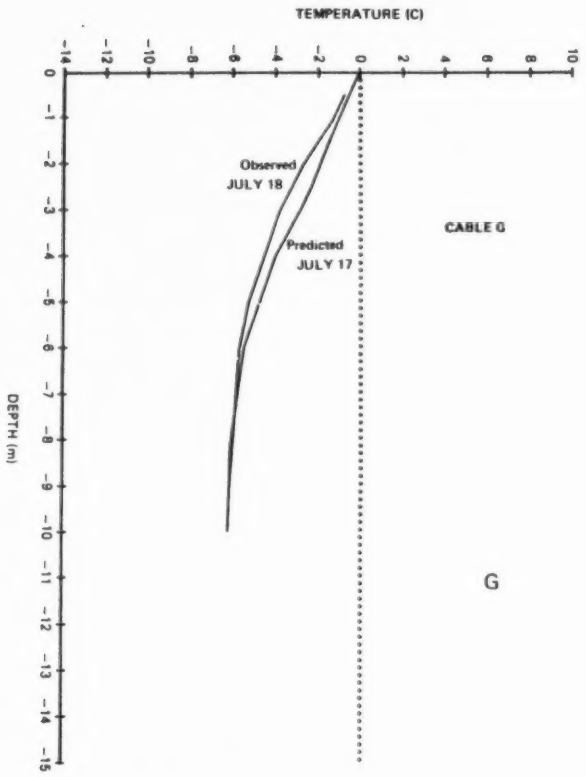
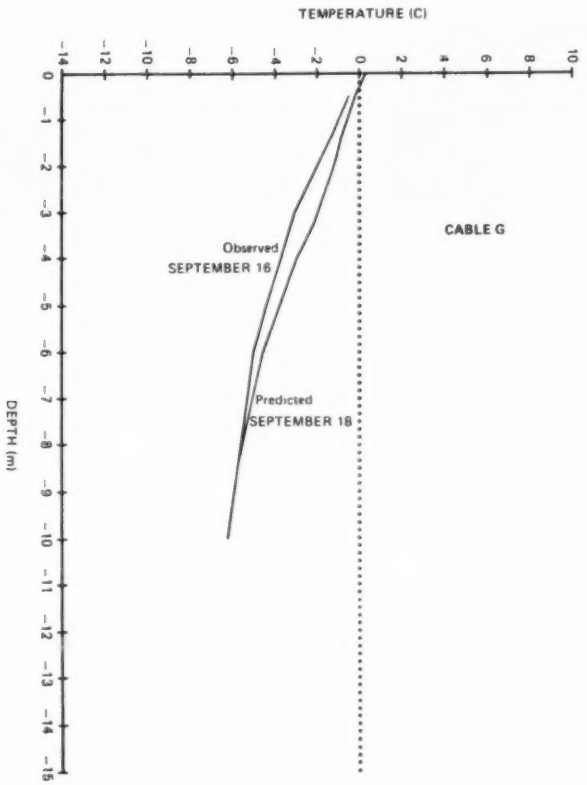
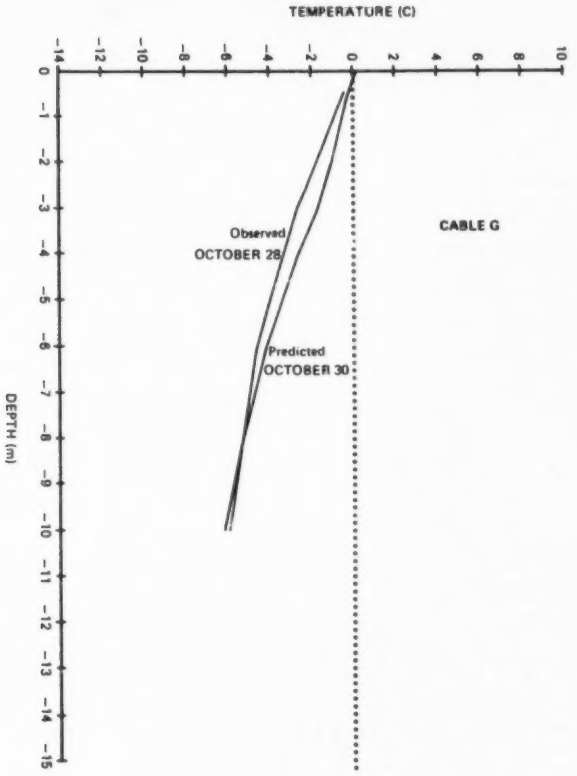
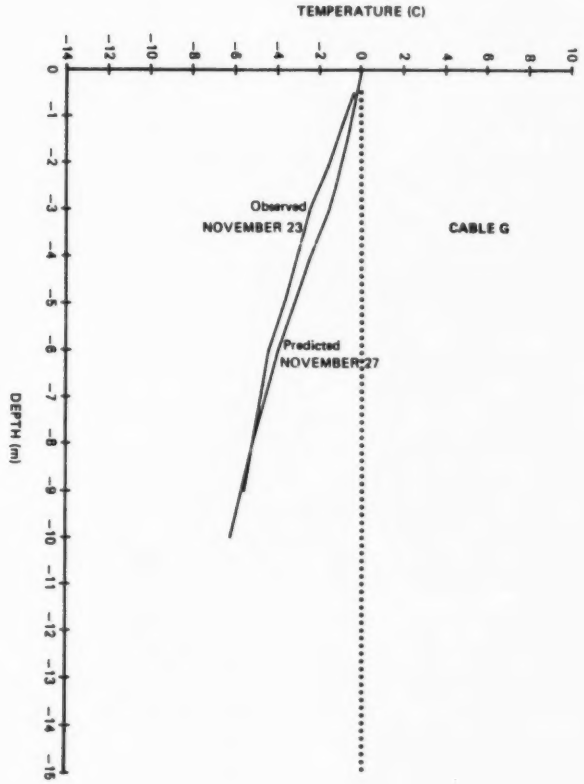
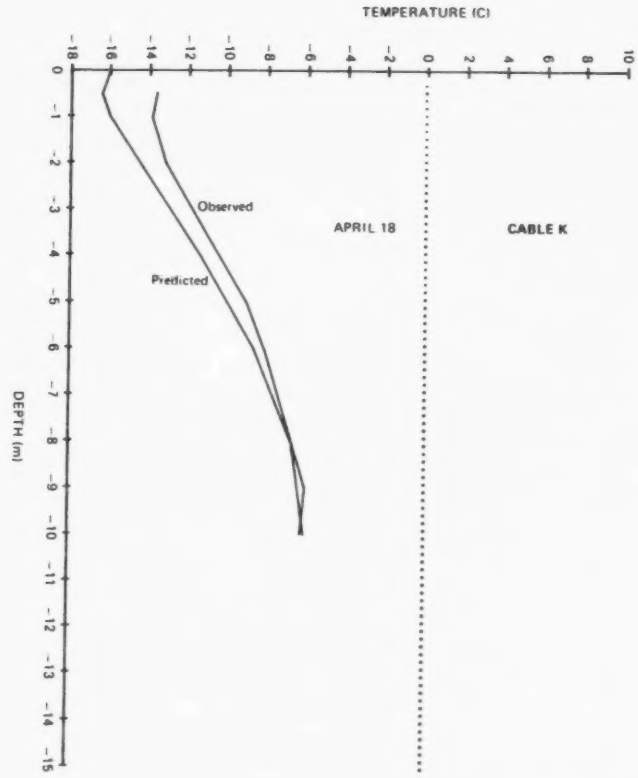
DEPTH (m)
Observed
JUNE 5
Predicted
CABLE G


TEMPERATURE (C)
DEPTH (m)
Observed
JULY 18
Predicted
JULY 17
CABLE G
G


TEMPERATURE (C)
DEPTH (m)
Observed
SEPTEMBER 16
Predicted
SEPTEMBER 18
CABLE G


TEMPERATURE (C)
DEPTH (m)
Observed
OCTOBER 28
Predicted
OCTOBER 30
CABLE G


TEMPERATURE (C)
DEPTH (m)
Observed
NOVEMBER 23
Predicted
NOVEMBER 27
CABLE G


TEMPERATURE (C)
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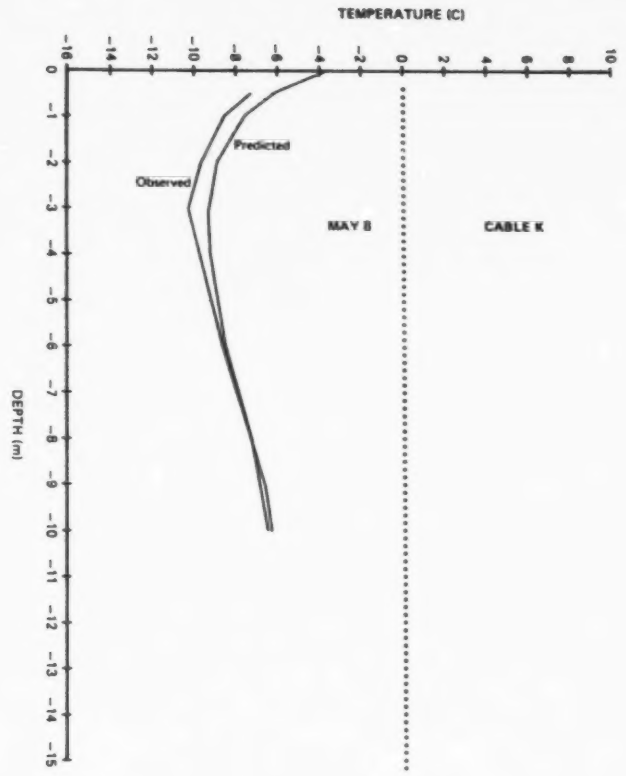
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
DEPTH (m)
Observed
Predicted
APRIL 18
CABLE K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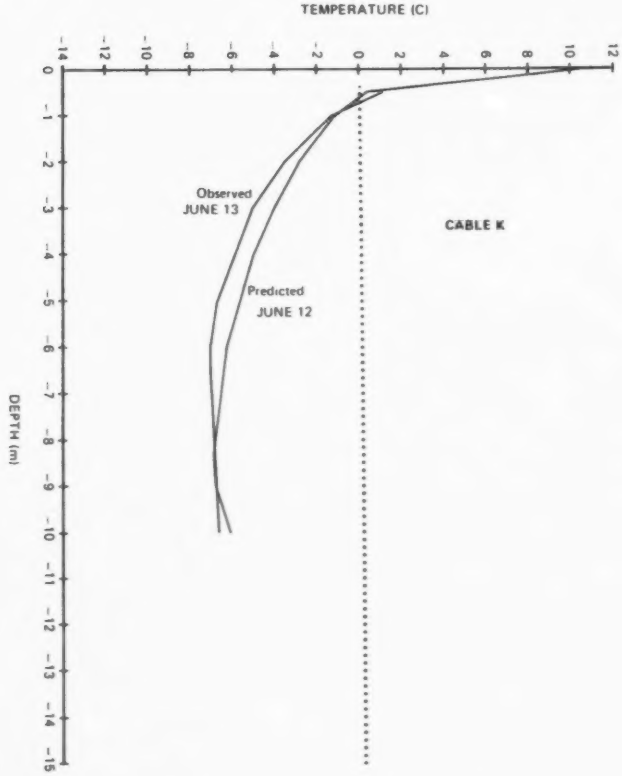
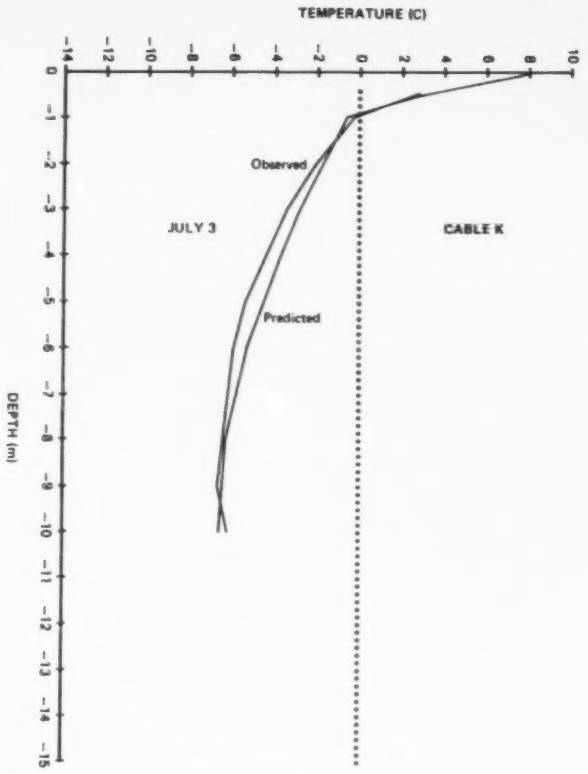
DEPTH (m)
Predicted
Observed
MAY 8
CABLE K


TEMPERATURE (C)
DEPTH (m)
Observed
JUNE 13
Predicted
JUNE 12
CABLE K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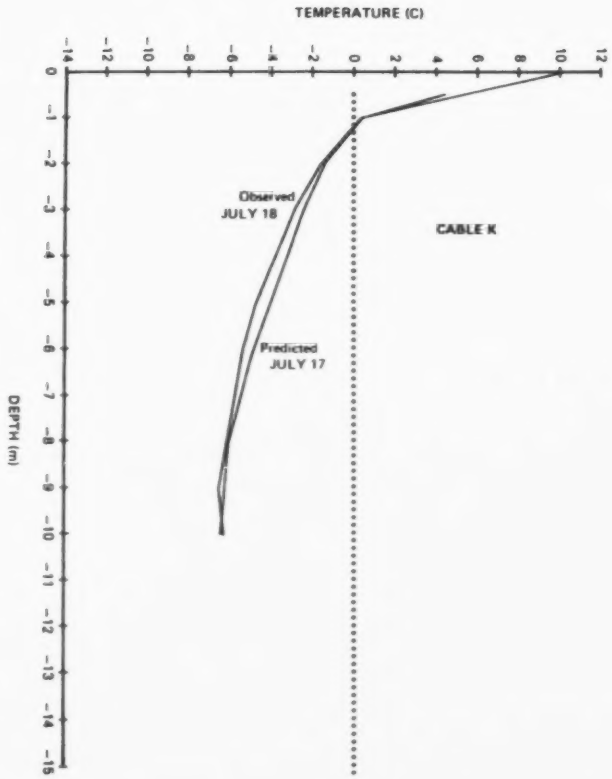
DEPTH (m)
Observed
Predicted
JULY 3
CABLE K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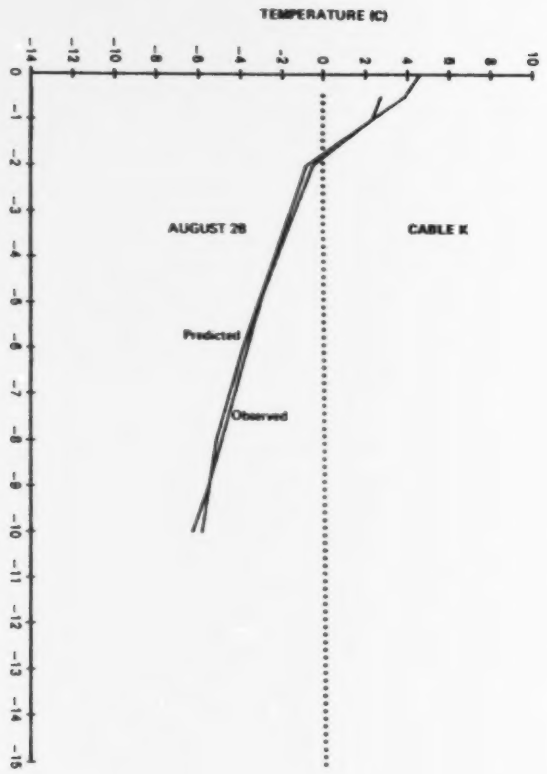
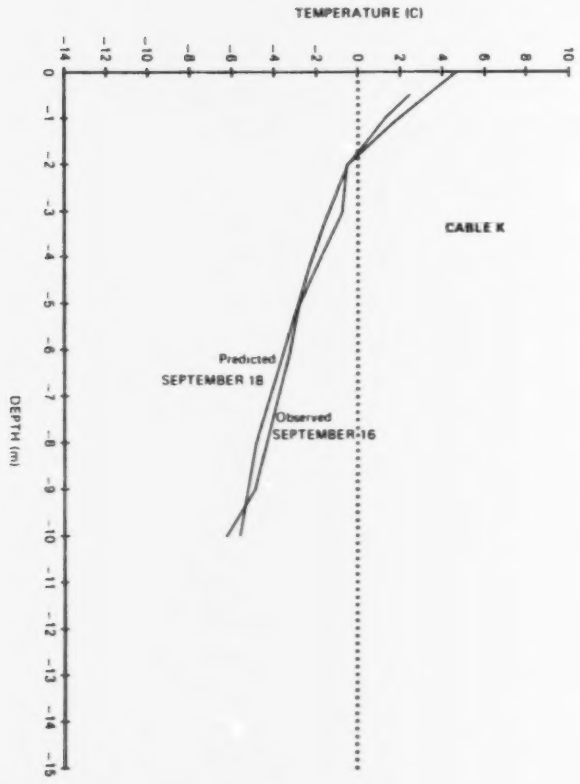
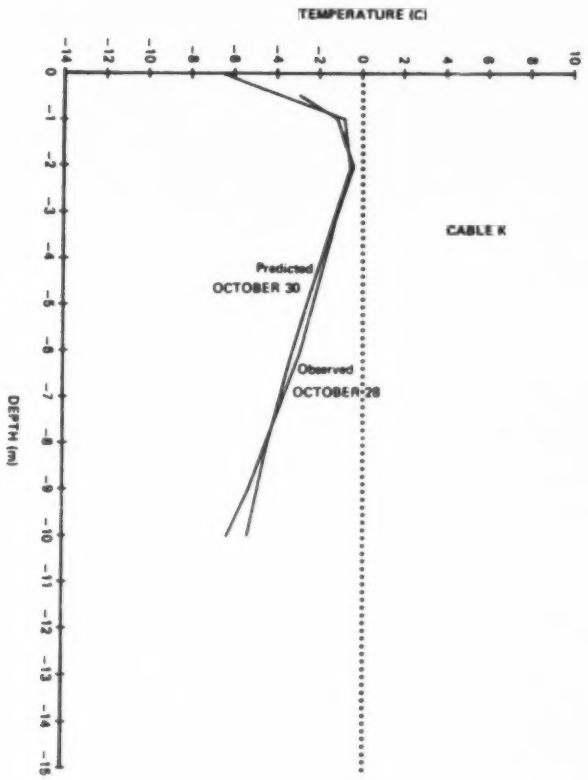
DEPTH (m)
Observed
JULY 18
Predicted
JULY 17
CABLE K


TEMPERATURE (C)
AUGUST 28
CABLE K
Predicted
Observed


TEMPERATURE (C)
DEPTH (m)
CABLE K
Predicted
SEPTEMBER 18
Observed
SEPTEMBER 16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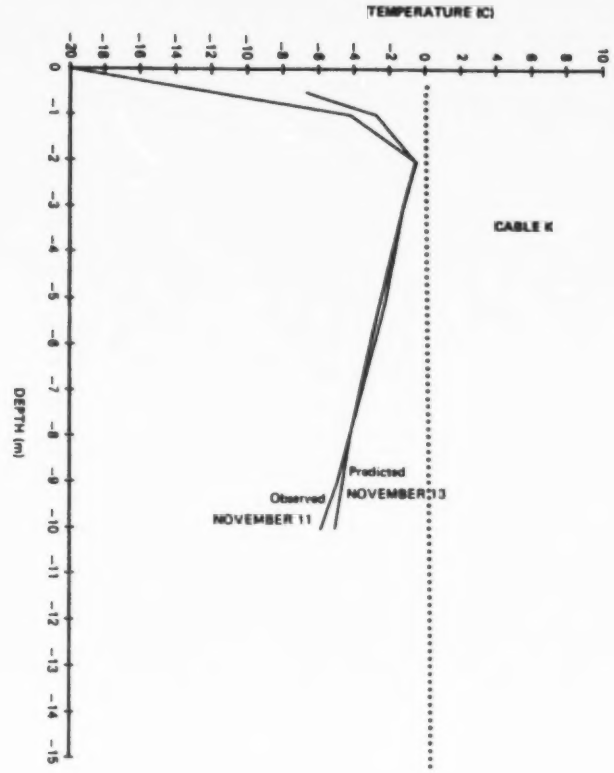
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
DEPTH (m)
CABLE K
Predicted
OCTOBER 30
Observed
OCTOBER 28


TEMPERATURE (C)
DEPTH (m)
CABLE K
Predicted
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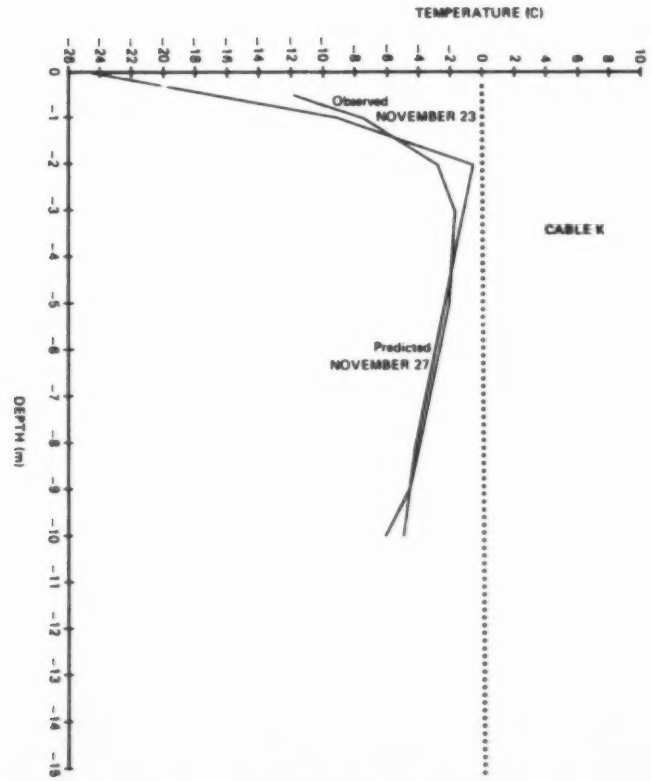
Observed
NOVEMBER 11


TEMPERATURE (C)
DEPTH (m)
Observed
NOVEMBER 23
CABLE K
Predicted
NOVEMBER 27

POOR

QUALITY

ORIGINAL